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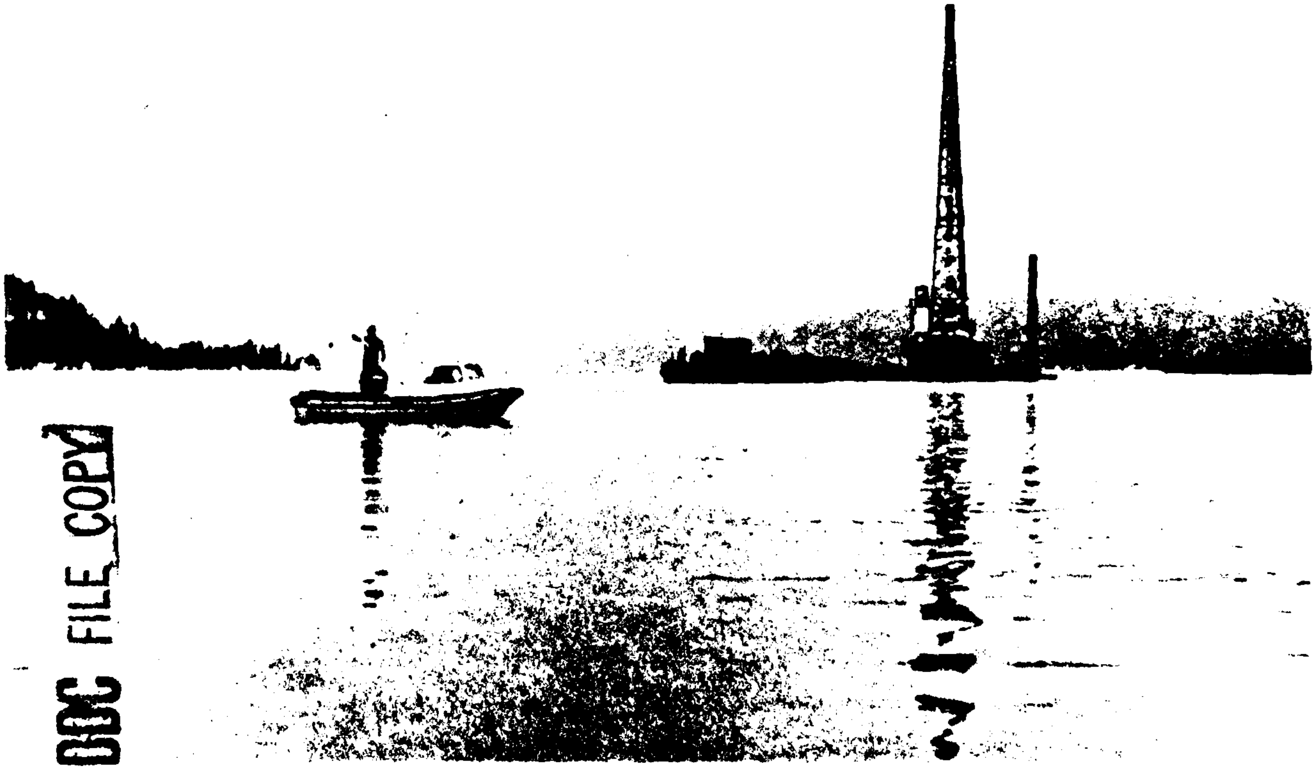
GRAYS HARBOR AND CHEHALIS RIVER

Improvements to Navigation Environmental Studies

A Review of Water Characteristics of Grays Harbor 1938-1979 and an Evaluation of Possible Effects of the Widening and Deepening Project upon Present Water Characteristics

By

LINCOLN C. LOEHR and EUGENE E. COLLIAS



DEPARTMENT OF OCEANOGRAPHY
UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

JANUARY 1981

SEATTLE DISTRICT
U.S. ARMY CORPS OF ENGINEERS
SEATTLE, WASHINGTON

Cover Photograph. Sampling water characteristics near an operating clamshell dredge.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The Seattle District U.S. Army Corps of Engineers is proposing to widen and deepen the navigation channel in Grays Harbor, Washington. The objectives of this report are 1) to evaluate the existing water characteristics of Grays Harbor, 2) to summarize these data, 3) to evaluate the possible impacts the proposed dredging project may have upon the water characteristics and 4) to evaluate mathematical models for use as predictive tools in describing the distribution of dissolved oxygen (DO).

Water characteristics data were obtained from many sources and covered the years from 1938 through 1979. Over 36,000 records were analyzed and are published as a separate appendix to this report.

Grays Harbor is a dynamic body with the water moving in response to the tides. Frequently during periods of low river flow a "DO sag" occurs from Hoquiam to Cosmopolis. The amount of DO in Grays Harbor has increased from 1975 to date because of improved methods of waste treatment practices by industry and municipalities.

Three mathematical models designed to predict the distribution of DO in Grays Harbor were examined. After careful review, the EPA model developed by Region X, Seattle office, was implemented. Output from the model did not reproduce the migratory nature of the "DO sag" nor the tidal periodicity observed in DO at a given location. Hence the results from this model are not suitable for use in applied problems.

It is the conclusion of the authors that the proposed widening and deepening of the navigation channel in Grays Harbor will have no significant impact upon the water characteristics of Grays Harbor.

UNIVERSITY OF WASHINGTON
DEPARTMENT OF OCEANOGRAPHY
SEATTLE, WASHINGTON 98195

A REVIEW OF WATER CHARACTERISTICS OF GRAYS HARBOR 1938-1979 AND AN EVALUATION OF POSSIBLE EFFECTS OF THE PROPOSED CHANNEL WIDENING AND DEEPENING PROJECT UPON PRESENT WATER CHARACTERISTICS

by

Lincoln C. Loehr and Eugene E. Collias

for

Seattle District
U.S. Army Corps of Engineers

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Approved by:

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ABSTRACT

The Seattle District U.S. Army Corps of Engineers is proposing to widen and deepen the navigation channel in Grays Harbor, Washington. The objectives of this report are: 1) to evaluate the existing water characteristics data of Grays Harbor, 2) to summarize these data, 3) to evaluate the possible impacts the proposed dredging project may have upon the water characteristics and 4) to evaluate selected mathematical models for use as predictive tools in describing the distribution of dissolved oxygen (DO).

Water characteristics data were obtained from the files of industry, government, and institutions of higher education. In all over 36,000 data records were analyzed. These data were reduced to a common format and are presented in an appendix to this report. All or part of this data (1,100 pages in all) may be obtained from the Seattle District for the cost of reproduction.

The movement of the water in Grays Harbor is very dynamic responding to the tides, winds, river flow, seasons, coastal upwelling and other factors. Frequently, during periods of low river flow, below 2,500 cfs, a "DO sag" occurs between Hoquiam to Cosmopolis. This "DO sag" is a dynamic feature moving as much as 8 miles in a 6-hour period as the tide changes from low to high or from high to low.

The concentration of DO in Grays Harbor has increased since 1975 because of improvements in waste treatment practices by industry and municipalities. Increased amounts of water released from the Wynoochee Resevoir into the Chehalis River has prevented the river flow at Aberdeen from rarely falling below 1,000 cfs. The flushing time of inner Grays Harbor will usually be less than five days even at minimum river flow.

Three mathematical models designed to predict the distribution of DO in Grays Harbor were examined. After careful review, it was decided to implement the model developed by Region X, Seattle Office, of the Environmental Protection Agency (EPA). This model was specifically developed for Grays Harbor. It included changes in water volume between low and high tide due to the extensive mud flats and incorporated many factors affecting DO. However, our analysis of the output from the model indicated that it does not reproduce the migratory nature of the "DO sag" nor the tidal periodicity observed in DO concentration at a given location. Hence, the results from this model must be viewed with skepticism. It is not suited for use in applied problems such as the widening and deepening project.

From our examination of the existing water characteristics data and from the results obtained from the physical model of Grays Harbor, *we conlcude that the proposed widening and deepening of the navigation channel will have no significant impact upon the water characteristics of Grays Harbor*. This conclusion is based upon the following facts: 1) Improved treatment of wastes by industry and municipalities since 1975 have removed much of the material responsible for biochemical oxygen demand. As a result the DO concentration in the inner portion of Grays Harbor has increased at all seasons and all river flows; 2) the proposed dredging will increase the volume of the navigation channel on the average by 9% with the largest change (27%) being confined to the turning basin area near Cosmopolis; and 3) a slight increase in residence time of the water near Cosmopolis may occur but this will be offset by the enhancement of the two-layer flow and by increase water volume to assimulate oxygen demanding substances. If the channel is dredged to a smaller size than planned, the small size will also have no significant impact.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

This study was made possible by a contract with the Seattle District U.S. Army Corps of Engineers.

The water characteristic data were obtained from many sources, including both industry and governmental agencies. Excellent cooperation was received from all parties. This cooperation was greatfully appreciated. It made our task much easier.

The authors wish to thank the many students and members of the professional staff of the Department of Oceanography who contributed to the success of this study. Steven Hobbs worked on the mathematical model and converted the source program supplied by EPA to the PRIME computer. Mary Usher and Meri Cooper keypunched over 36,000 data cards and then assisted in proofreading these data. William Weigand gathered and assisted in evaluation of the water characteristic data from stations offshore of Grays Harbor. David English assisted in making the original drawings of the numerous figures and Donald Doyle, Richard Cromoga, and Noel McGary prepared the final illustrations. Dr. Alyn Duxbury provided many inputs and guidance throughout the project. The final typing was done by Carolynn Padgett.

A REVIEW OF WATER CHARACTERISTICS OF GRAYS HARBOR 1938-1979 AND AN EVALUATION OF POSSIBLE EFFECTS OF THE PROPOSED CHANNEL WIDENING AND DEEPENING PROJECT UPON PRESENT WATER CHARACTERISTICS

by

Lincoln C. Loehr and Eugene E. Collias

1. INTRODUCTION

1.1 *Background and Objectives*

The Seattle District of the U.S. Army Corps of Engineers is conducting a feasibility study for a proposed widening and deepening of the navigation channel in Grays Harbor, Washington. An integral part of this study is a detailed review of the existing data and literature concerning the water characteristics for the whole of Grays Harbor and the waters of the Pacific Ocean immediately adjacent to its mouth. In November 1979, the Department of Oceanography of the University of Washington entered into formal contractual agreement with the Corps to conduct this study.

The study had four objectives:

1. To review the existing water characteristics data for Grays Harbor and the waters of the Pacific Ocean immediately adjacent to its mouth;
2. To summarize these data and reduce them to a common format;
3. To evaluate the impacts of the proposed dredging upon the water characteristics of Grays Harbor; and
4. To evaluate several mathematical models that may provide an estimate of the dissolved oxygen content of the waters of Grays Harbor.

The intent of this study was not to obtain new data, so no field work was conducted. The literature review was to emphasize the data from 1965 to date, but a summary was to be given of all available data.

1.2 *Description of the Study Area*

Grays Harbor, Washington, is a large, pear-shaped estuary located on the southwest coast of the State of Washington (see Fig. 1-1 for location) and was formed by the drowning of the seaward portion of the Chehalis River valley. It is 46 miles north of the mouth of the Columbia River and 135 miles south of Cape Flattery.

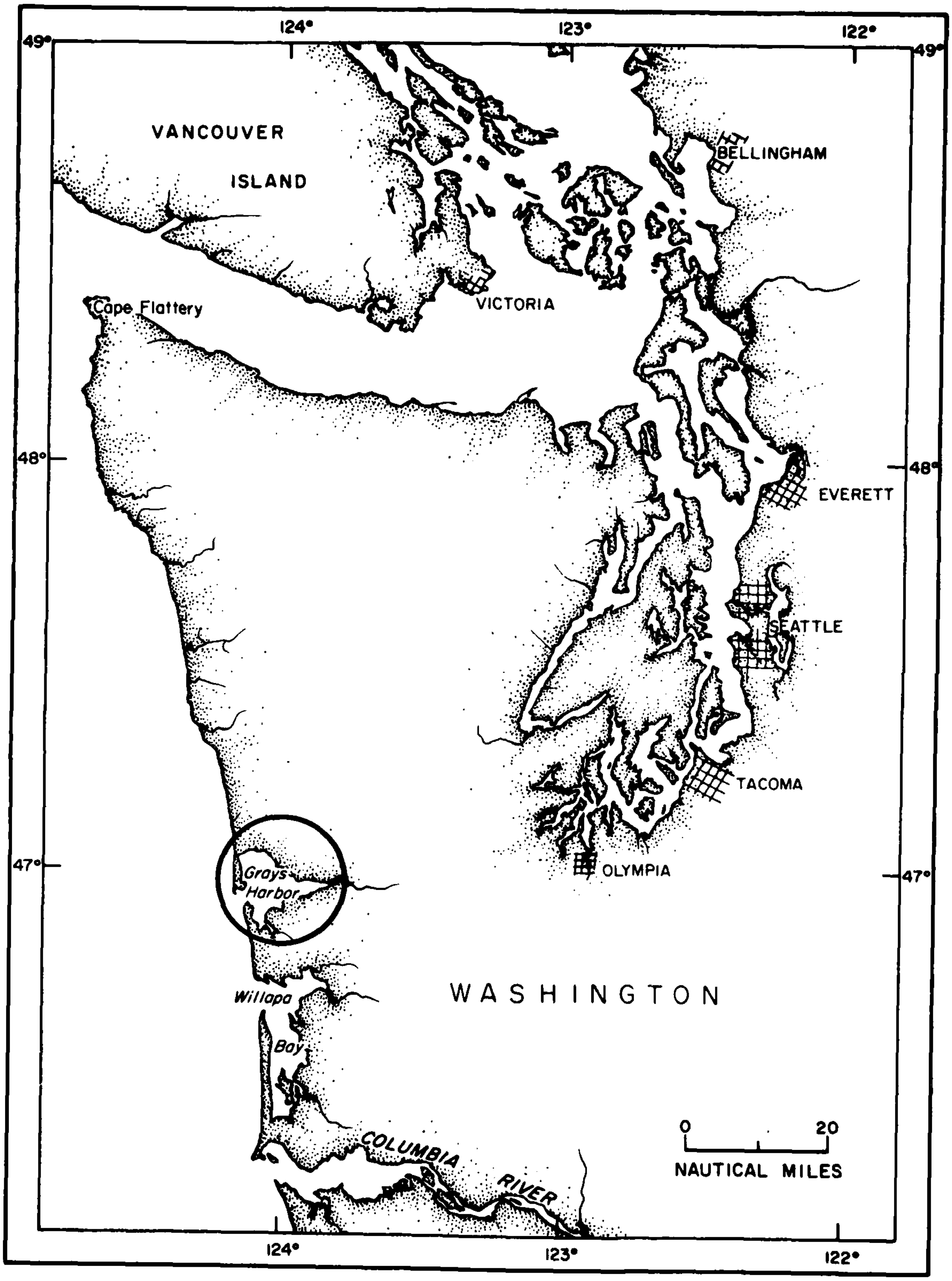


Figure 1-1. Location of Grays Harbor

Grays Harbor is bounded on the north, east, and south by hills of low relief and is separated from the Pacific Ocean by two narrow, sandy peninsulas. The entrance is 8,050 feet wide and lies between Point Brown on the north and Point Chehalis on the south (see Fig. 1-2). Moving landward, the estuary may be divided into two major areas: the outer harbor extending from the Pacific Ocean east to Point New and the inner harbor extending east from Point New to Cosmopolis. For convenience, these two major areas were further subdivided into 15 segments. These subdivisions and associated names are presented in Figure 1-3. The names will be used throughout this report.

Grays Harbor is characterized by expansive mud flats, which are bare at zero tide, and intervening channels that have been formed by the discharge of the many rivers and creeks entering into the estuary. The most important of these channels are North Channel and South Channel extending from the deep water near the estuary entrance to Cow Point. The principal rivers entering Grays Harbor are the Chehalis, Humptulips, Hoquiam, Wishkah, Johns, and Elk. Except for the Chehalis and the lower reaches of the Hoquiam, the tributary rivers are not important for navigation.

The surface area of Grays Harbor from its mouth landward to Montesano is 1.06×10^9 ft^2 and the volume is 13.66×10^9 ft^3 at mean lower low water (MLLW) (Stein, Denison, and Peterson, 1966). At mean higher high water (MHHW) this changes to 2.53×10^9 ft^2 and 37.13×10^9 ft^3, respectively. Hence, 58% of the high tide surface area is attributed to the mud flats. A summary of the area-volume relationships for Grays Harbor is given in Table 1-1.

The U.S. Army Corps of Engineers proposes to widen and deepen the navigation channel by substantial amounts. The proposal is to dredge the channel to a depth of 45 feet below MLLW in the Entrance Reach and to a depth of 40 feet from Westport to Cosmopolis. The width in the Entrance Reach will taper from 1,200 feet to 600 feet. North of Westport the channel width will be 400 feet to the west end of Hoquiam Reach, where it will narrow to 350 feet. A turning basin near Cow Point will be dredged to a 1,000 foot square with a depth of 40 feet. From Aberdeen Reach to near Cosmopolis the channel width will be 300 feet. North of Cosmopolis a turning basin 800 by 1,000 by 40 feet deep will be dredged. The existing channel begins about two miles landward of the entrance and has an average width of 350 feet to Aberdeen Reach where it decreases to 200 feet. The average depth of the existing channel varies from 35 feet at the seaward end to 28 feet near Cosmopolis.

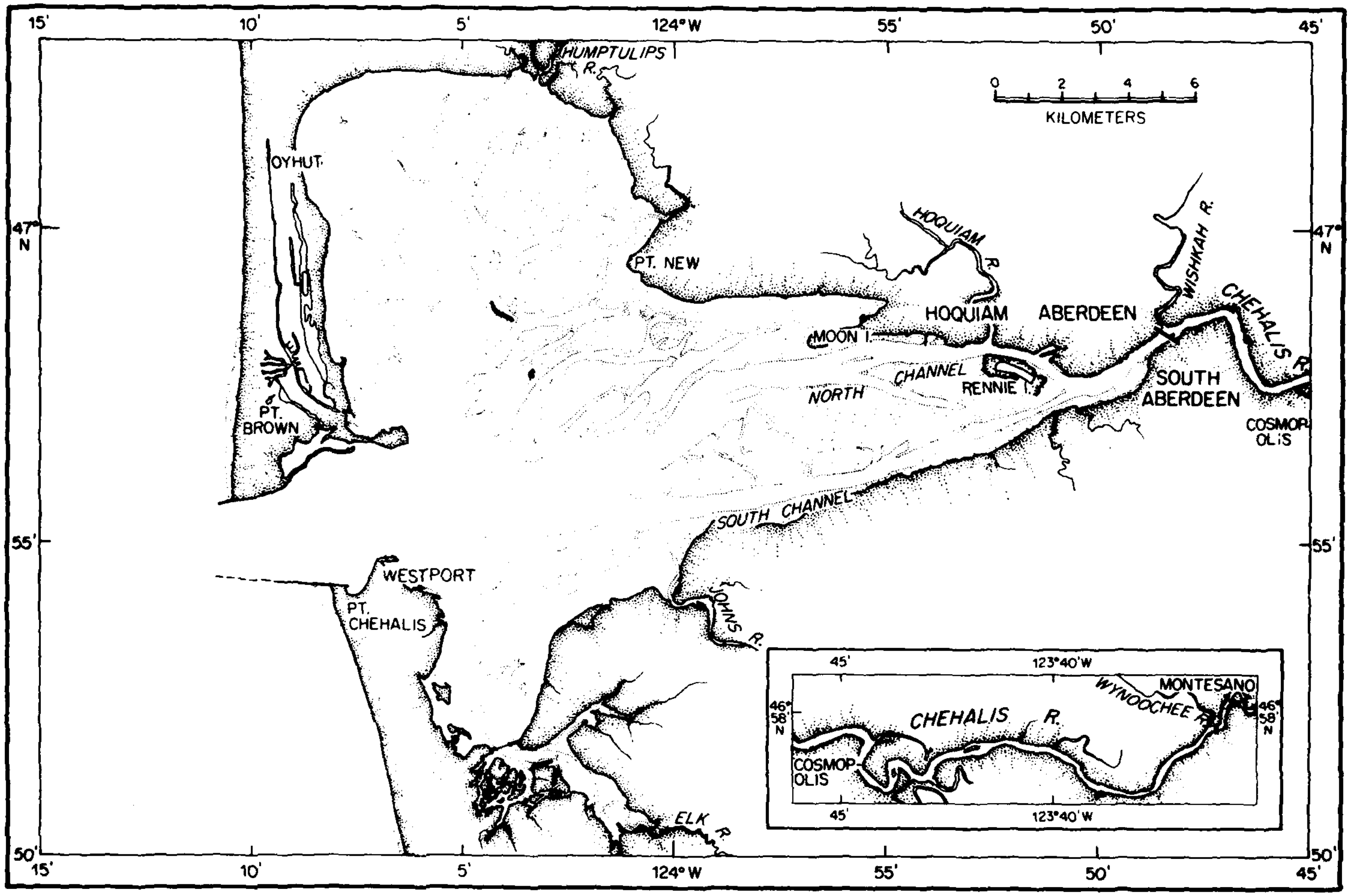


Figure 1-2. Grays Harbor details

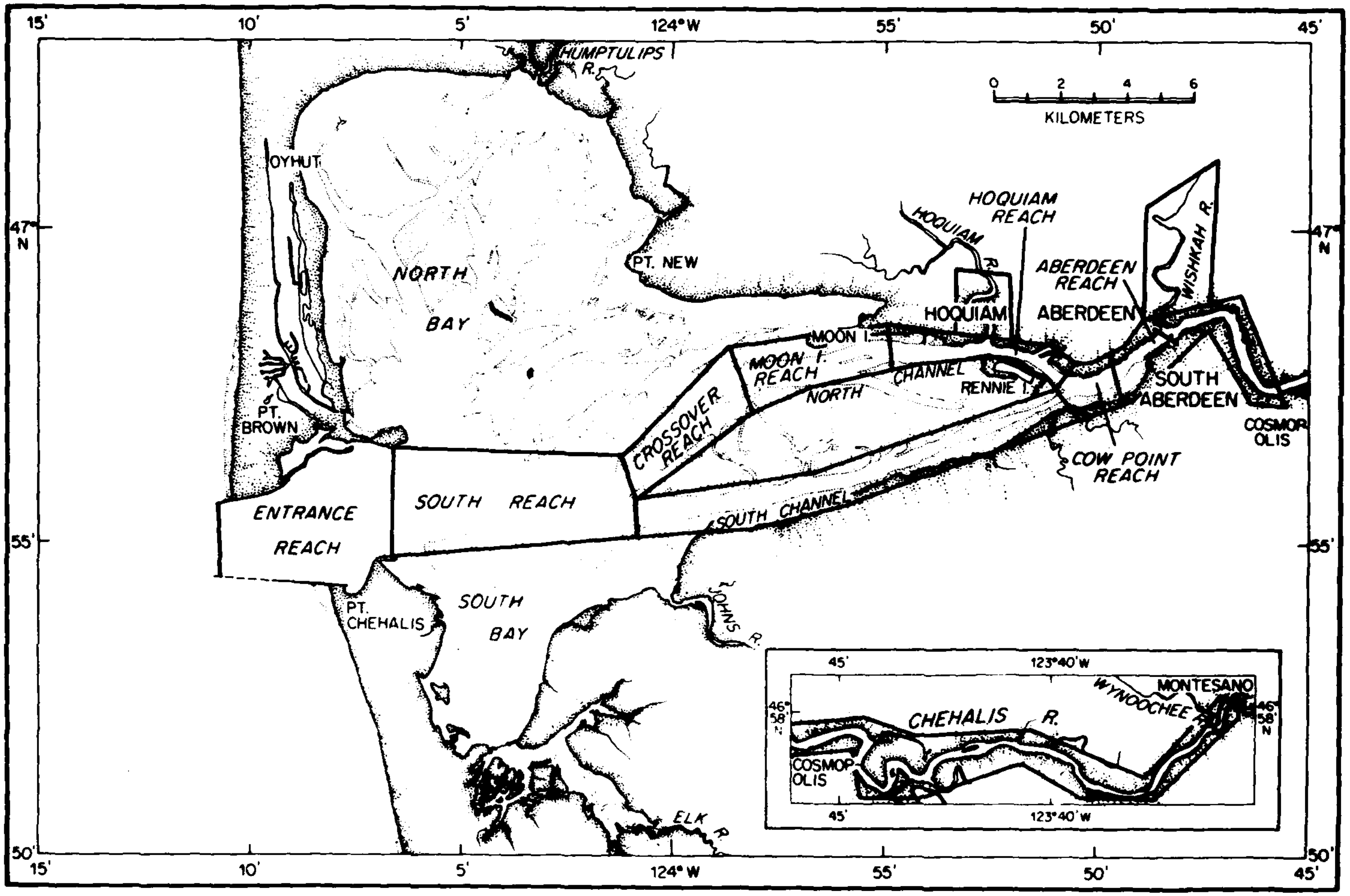


Figure 1-3. Subdivisions of Grays Harbor

TABLE 1-1

GRAYS HARBOR SURFACE AREA
AND WATER VOLUME RELATIONSHIPS

A Tabulation of the Total Surface
Areas and Respective Water Volumes for
Different Mean Tide Phases of Grays Harbor

Tide Phase	Total Water Surface Area in Square Feet	Total Volume in Cubic Feet
Mean Lower Low	1.06×10^9	13.66×10^9
Mean Low	1.27×10^9	15.27×10^9
Mean	1.85×10^9	22.77×10^9
Mean High	2.40×10^9	33.17×10^9
Mean Higher High	2.53×10^9	37.13×10^9

After Stein, Denison and Peterson (1966)

2. REVIEW OF WATER CHARACTERISTIC DATA

2.1 *Introduction*

A large portion of this study involved the preparation of a water characteristic (or water quality) data base for Grays Harbor. In all, the data base included over 36,000 records. One record of water characteristic data consists of the parameters measured at a single depth and at a given time. A station is a geographic location where one or more data records were obtained. These data are presented in Appendix A titled "Physical and Chemical Oceanographic Data from Grays Harbor, 1938-1979", by Collias and Loehr (1980).

The earliest water characteristic data from Grays Harbor were obtained in 1938 by Eriksen and Townsend (1940). The largest amount of data were obtained by industry between 1965 and 1976. Table 2-1 is a listing of the number of data records by year from 1938 through 1979. The decrease in data records after 1974 reflects a decrease in sampling by industry.

2.2 *Sources of Data*

Water characteristic data obtained for this study required searching the libraries and records of governmental agencies, private industry, and educational institutions. By far the largest amount of data on water characteristics from Grays Harbor was collected by and obtained from the two pulp and paper mills currently operating in Grays Harbor, which are owned by ITT Rayonier, Inc. and Weyerhaeuser Company. Although many of these data were collected to satisfy the requirements of governmental agencies, the mills initiated other studies in which water characteristics were determined.

The earliest comprehensive study of the waters of Grays Harbor was conducted by Eriksen and Townsend (1940). Most of the station locations and identifying numbers presently in use by industry and government were derived from this report. The Washington State Department of Ecology (WDE), and its predecessor, the Washington Pollution Control Commission, collected water quality data from Grays Harbor as related to enforcement of regulations. The WDE also serves as a repository for many of the industries' data.

Personnel from Grays Harbor College have been involved in monitoring water characteristics during dredging operations. In addition, they obtained water characteristics near Terminal 4 at Cow Point during a period when antisiltation devices were being tested. Water quality data related to studies of shellfish growth were obtained by the Washington State Department of Fisheries. Data in the Pacific Ocean near the mouth of Grays Harbor were obtained by the University of Washington.

TABLE 2-1

NUMBER OF WATER CHARACTERISTICS DATA RECORDS IN GRAYS HARBOR BY YEAR COLLECTED

YEAR	NUMBER OF DATA RECORDS	YEAR	NUMBER OF DATA RECORDS
1938	233	1966	2,013
1939	86	1967	3,996
1950	215	1968	3,804
1951	1,053	1969	3,568
1952	634	1970	3,650
1953	839	1971	1,623
1954	239	1972	3,271
1955	264	1973	1,347
1956	199	1974	1,856
1957	343	1975	1,443
1962	63	1975	1,371
1963	332	1977	645
1964	526	1978	453
1965	1,922	1979	448

TOTAL NUMBER OF RECORDS = 36,436

Note: A data record represents the water characteristics at one depth. Data for a station may contain from one to four data records.

2.3 *Water Characteristics Selected for Documentation*

Water characteristics selected for presentation in this report and in the data appendix include: sampling depth, temperature, salinity, density, dissolved oxygen concentration (DO), percent oxygen saturation, 5-day biological oxygen demand (BOD), spent sulfite liquor concentration (SSL), pH, and turbidity. These were the parameters most frequently measured. Sometimes other properties were measured such as nutrients, chlorophyl, productivity, etc., and were identified in the data report. Because salinity (S) is the standard representation for the salt content of sea water, any chlorinity data were converted to salinity by the relationship

$$S = 1.805\ Cl + 0.03 \qquad (2.1)$$

where Cl is the chlorinity in parts per thousand (‰).

The depth of the samples usually was reported in feet. But sometimes the depths were simply described as surface (S), middle (M), or bottom (B), or reported as a distance in feet from the bottom or surface. We have reported all depths in feet and have retained the designations as reported in the original reports. If depths were reported in meters they were converted to feet for the final report.

2.4 *Reformatting of Data*

Each investigator presented the data in a different format. To simplify the use and presentation of the data, a common format was prepared and each of the selected parameters converted to the same units and precision. All parameters were reported to the nearest 0.1 unit except SSL values were reported to the nearest whole unit. This is the maximum precision justified because of the rapid changes that occur both in time and space within Grays Harbor. In addition to the parameters listed in Section 2.3, river flow and tidal information were computed for each data record and included in the final presentation of the data.

2.5 *Referencing of the Data*

Water characteristics must be keyed to geographic location, time, tide height and stage, and river discharge to be used in any analyses. To do this, the following system was developed.

2.5.1 *Station Locations and Names:* The station locations and names used in this report are for the most part those first designated by Eriksen and Townsend (1940). But many subsequent investigators developed their

own names. So whenever a station location was found to be identical with one of Eriksen and Townsend, it was renamed accordingly. If a station location did not match one of Eriksen and Townsend, the name used was that one first reported in the literature. Thus the resulting station's designators are a combination of alphameric characters and follow no logical sequence. A detailed listing of locations and station designators will be presented in the data appendix, and are shown in Figures 2-1 and 2-2.

2.5.2 *Dates and Times:* Dates and times are essential for any oceanographic station, especially in such a dynamic region as Grays Harbor. If the date was not listed in the original data, the data were discarded. The actual time of day is necessary to relate the sample to a given tide stage. However, very few investigators stated whether the times were reported in Pacific Standard Time or in Daylight Time. Conversations with many of the investigators who did much of the actual field work concluded that "wrist watch" time was used. We have reported the times as originally specified in the data reports but have determined if Standard or Daylight Time was used. The determination as to which one was made according to the dates listed in Table 2-2.

2.5.3 *Tide Height and Stage:* Many of the field programs were developed around either low or high water at Aberdeen and considerable bias is incorporated into the data because of tide stage. The tide height and stage incorporated into the final data format were computed from the predicted tides at Aberdeen. These predictions are available from the Tide Tables published by the National Ocean Survey. A computer program was written that took the actual time of the sample, corrected for Daylight Time if necessary, and then computed the predicted height, range, and stage. The stage is designated as

H for high water
L for low water
R for a rising tide (flood), and
F for a falling tide (ebb).

2.5.4 *Chehalis River Flow:* The input of fresh water into Grays Harbor is very important to the circulation, flushing, and dynamics of the estuary. Water characteristics are also affected to a considerable extent by the river flow. The river discharge at Aberdeen was calculated and recorded for each data record according to the method described in Section 3.1. By including the river flow on each data record, it is possible to correlate

TABLE 2-2

DAYLIGHT SAVINGS TIME FOR GRAYS HARBOR

1938	none	1965	25 April--31 October
1939	none	1966	24 April--30 October
1950	30 April--24 September	1967	30 April--29 October
1951	29 April--30 September *	1968	28 April--27 October
1952	none	1969	27 April--26 October
1953	none	1970	26 April--25 October
1954	none	1971	25 April--24 October
1955	none	1972	30 April--29 October
1956	none	1973	29 April--28 October
1957	none	1974	28 April--27 October
1958	none	1975	25 February--26 October **
1959	none	1976	25 April--31 October
1960	none	1977	24 April--30 October
1961	30 April--24 September	1978	30 April--29 October
1962	29 April--30 September	1979	29 April--28 October
1963	28 April--27 October	1980	27 April--26 October
1964	26 April--25 October		

* Montesano remained on standard time in 1951 while Hoquiam and Aberdeen switched to daylight savings time.

** Daylight savings time started early because of energy shortage, reference was Seattle Times, February 24, 1975.

Reference for most of this table was Doane (1973).

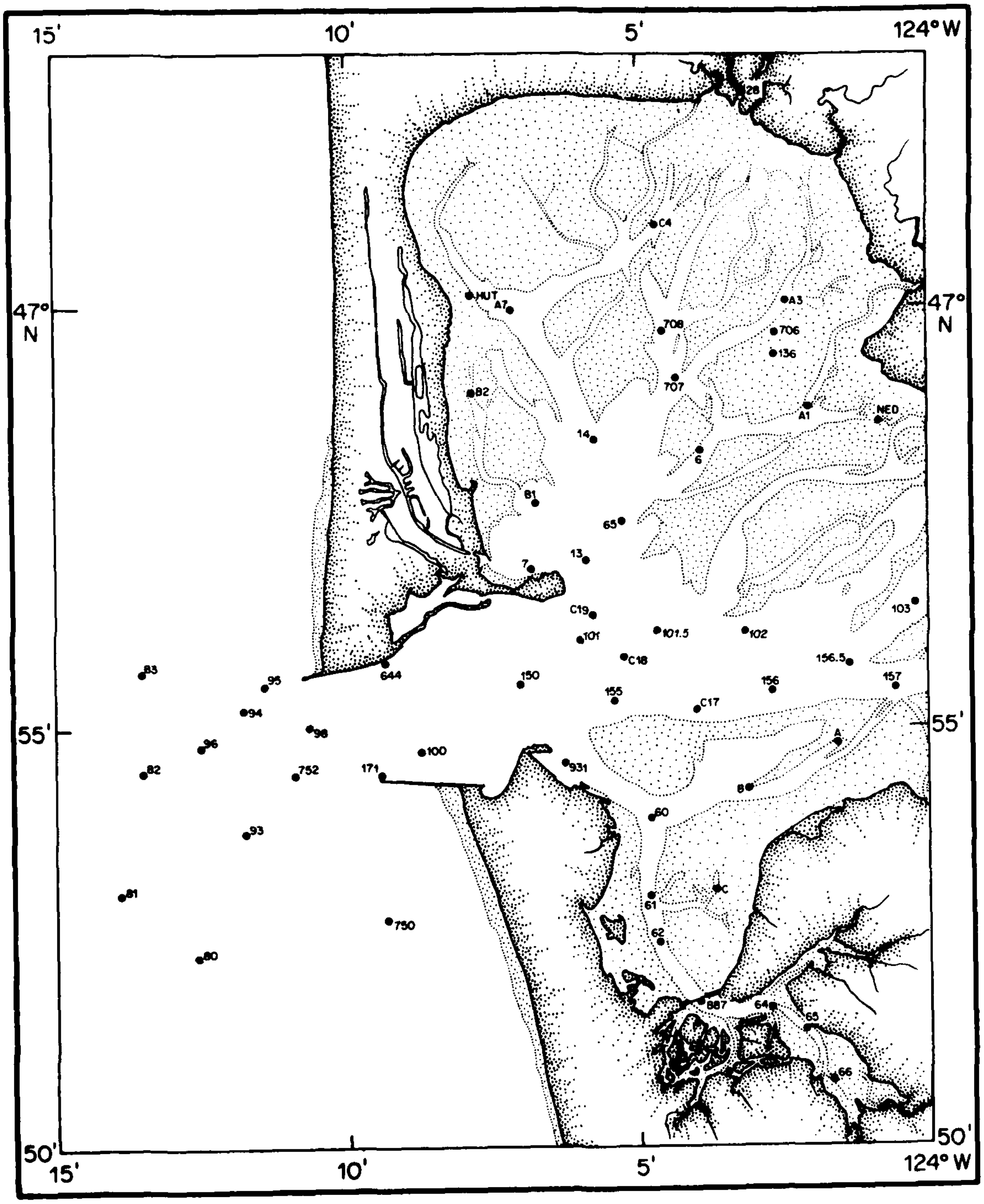


Figure 2-1. Oceanographic stations in outer Grays Harbor

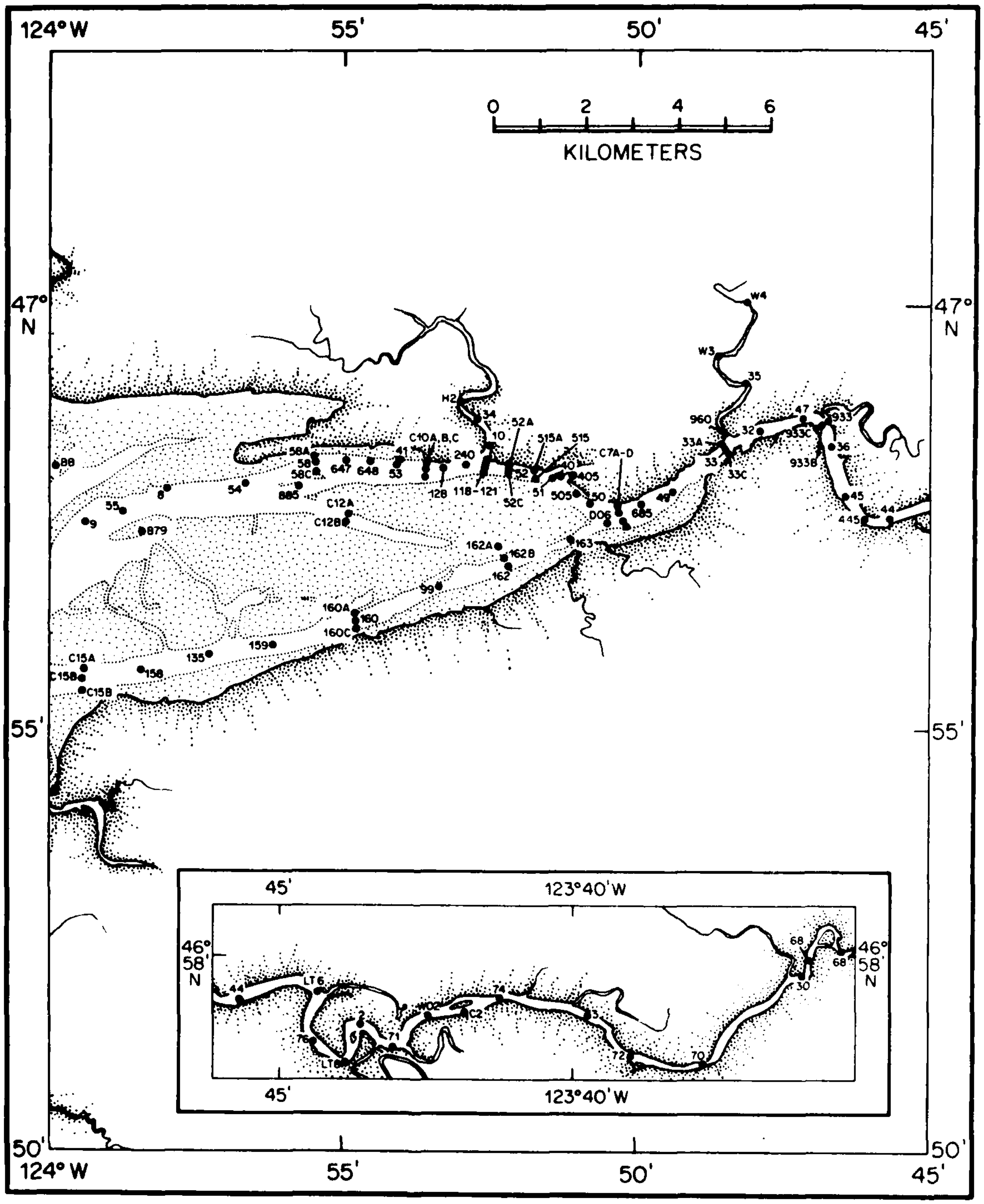


Figure 2-2. Oceanographic stations in inner Grays Harbor

water characteristics with river discharge and to evaluate the merit of using river flow to establish monitoring requirements and limits upon dredging activities.

2.6 *Quality of Data*

2.6.1 *Sampling and Analytical Techniques:* Many data reports did not describe the scientific methods used to obtain and analyze the samples. In cases where documentation of methods could not be obtained, the data were carefully examined before acceptance or rejection.

Considerations used to evaluate the data were: 1) the type of physical and chemical methods used; 2) if probes were used, the type used and methods of calibration; 3) the level of experience and training of the personnel collecting the data, and 4) similarity of this set of data to data obtained either at the same time or at similar season, river and tide condition.

Probes for the direct determination of temperature, salinity and DO can be very useful because they permit the rapid acquisition of data. However, their use poses a question of reliability and accuracy especially for the determination of DO. Most DO probes are difficult to maintain and require frequent calibration or comparison with the accepted Winkler determination of DO. Hence, any data obtained with a probe were carefully examined before acceptance.

2.6.2 *Emphasis of the Sampling Program:* The purpose of the sampling programs varied with each set of data. By far the largest amount of data was obtained by industry to satisfy requirements imposed by regulatory agencies. As a result, these data were either obtained near high or low tide. Sometimes a program was so specific or narrow in scope that it was not useful in the documentation of long-term changes in water properties.

2.7 *Data Excluded from the Data Base*

Considerable amounts of data collected by Grays Harbor College were not included in the data base because the nature of their sampling programs yielded data that were not germane to the objectives of this study.

3. FACTORS AFFECTING WATER CHARACTERISTICS

3.1 *Freshwater Sources*

Freshwater entering into Grays Harbor is derived from six rivers (Chehalis, Humptulips, Hoquiam, Wishkah, Johns, and Elk) that have a combined drainage basin of 2,550 square statute miles. Areas of the individual basins are presented in Table 3-1. The rivers feeding Grays Harbor have very little drainage area extending into the higher elevations of the Olympic Mountains so the river flow closely follows the precipitation. Maximum runoff is observed in December and January when rainfall is greatest and minimum runoff occurs from June through September when rainfall is least.

The total flow of the Chehalis River at Aberdeen is not monitored by the U.S. Geological Survey because of tidal influence. Hence, for this study it was necessary to estimate the flow at Aberdeen. To make this estimate the following equation was used (Hess, 1978):

$$\begin{matrix}\text{Flow at}\\ \text{Aberdeen}\end{matrix} = \left(\begin{matrix}\text{Flow of the}\\ \text{Chehalis at}\\ \text{Grand Mound}\end{matrix} + \text{Wynoochee} + \text{Satsop}\right) \times 1.38 \qquad (3.1)$$

These three locations correspond to the U.S. Geological Survey river gaging stations numbered 12027500, 12037400, and 12035000. Equation (3.1) was valid until the time the dam on the Wynoochee River was completed and Lake Wynoochee filled. After 1 July 1975, the flow of the Chehalis at Aberdeen is best estimated as

$$\begin{matrix}\text{Flow at}\\ \text{Aberdeen}\end{matrix} = \left(\begin{matrix}\text{Chehalis at}\\ \text{Grand Mound}\end{matrix} + \text{Satsop}\right) \times 1.5 + \text{Wynoochee} \qquad (3.2)$$

The two equations were compared and it was determined that on the average there was less than 3% difference. To simplify calculations of river flow used in this report, the flow of the Chehalis at Aberdeen was computed using equation (3.1) for all the years, recognizing that a small discrepancy will occur after 1 July 1975.

The river flow at Aberdeen is important because the Washington State Department of Ecology (WDE) has required monitoring of water characteristics during dredging, especially dissolved oxygen and turbidity, when the river flow drops below 2,500 cubic feet per second (cfs).

TABLE 3-1
RIVER BASIN DRAINAGE AREAS
FOR GRAYS HARBOR

Basin	Drainage Area (sq. statute mi.)
Chehalis (above Wishkah R.)*	2012.0
Wishkah	102.0
Hoquiam	90.2
Humptulips	245.0
Johns	31.3
Elk	18.2
Miscellaneous	51.4
TOTAL	2550.1

*Includes the Satsop and Wynoochee River subbasins.

Source: Barrick, 1976.

3.2 *Municipal and Industrial Sources of Freshwater*

The cities of Montesano, Cosmopolis, and Aberdeen discharge their municipal wastes directly into the Chehalis River after treatment. Hoquiam discharges its municipal wastes into the inner harbor off Moon Island (west of station 53). The two pulp mills discharge their effluent near Rennie Island (stations 52 and 163). The combined daily discharge rate in July 1977 for the municipalities averaged only 4.3 cfs (2.78 mgd) and that of the two pulp mills was 77 cfs (50 mgd). These volumes are small compared to the river flow which at that time was 1,200 cfs. River flow varies from slightly less than 1,000 cfs to over 50,000 cfs while the waste flow remains about the same. Even though the contribution of the wastes is small in comparison to the river flow, they have a definite chemical impact upon the waters of the estuary. In developing a mathematical model to predict the distribution of DO in Grays Harbor, all waste discharges and their respective chemical properties must be considered..

3.3 *Salt Water Sources and Coastal Upwelling*

The salt water source for Grays Harbor is the Pacific Ocean. Pacific Ocean water, from varying depths depending upon season, enters Grays Harbor at its entrance. In June, the winds off the Washington coast shift from a dominant southwesterly flow to a northwesterly to northerly flow. North winds will cause cooler, lower DO and higher nutrient content oceanic water from a considerable depth below the surface to be forced upward, a process known as upwelling. When upwelling is intense, upwelled oceanic water from depth will enter Grays Harbor causing a rapid and marked reduction in temperature and DO of the waters in the Entrance Reach. Some of this upwelled water will be transported along the bottom towards the head of the estuary.

Coastal upwelling is most dramatic during summer when river flow is low. The natural reduction of DO due to upwelling plus any reduction in DO by biochemical oxygen demand (BOD) and chemical oxygen demand (COD) may cause the DO of the waters in the outer harbor to be reduced below the 5 ppm (parts per million) minimum established WDE for Grays Harbor in the water quality standards of the state. Unfortunately, only the studies conducted by Pearson and Gotaas for ITT Rayonier in the early 1950's included water sampling in the outer harbor on a regular basis. Thus, from the available data, it is difficult to determine just when upwelling begins and ends and how influential it is in the overall dynamics of Grays Harbor.

The relationship between temperature and DO in the incoming oceanic water at the Entrance Reach is shown in Figure 3-1. The lowest DO observed was less than 3 ppm and the corresponding temperature was less than 10°C, indicating that this was upwelled water.

The average DO for three different depth increments obtained from all the oceanographic data taken offshore of Grays Harbor seaward to 124°23'N longitude and between latitudes 46°45'N and 47°07'N is presented in Figure 3-2. These values are averages with the number of points for each month shown in parentheses below the month.

Profiles of DO and density obtained from two or more stations taken along east-west lines off of or just north of Grays Harbor are shown in Figures 3-3 through 3-8. A location sketch is shown in each figure. The DO in these figures is presented as milliliters per liter (ml/l). To compare these data with those reported for the rest of Grays Harbor, it is necessary to multiply these values by 1.43 to obtain parts per million or milligrams of DO per liter.

Upwelling was evident on three cruises. This was evident on 11 July 1962 (Fig. 3-3) as the lines of equal density (isopycnals) slope upwards towards the coast. On 18 April 1977 upwelling was evident below 20 m, while the surface was covered with freshwater, probably from the Columbia River (Fig. 3-7). On 9 August 1977 (Fig. 3-8) upwelling is quite pronounced, with the DO at 20 m being less than 2.0 ml/l (2.9 ppm) 5 km from shore. The remainder of the cruises were taken when upwelling would not normally be present.

A major problem arises in trying to quantify the impact of coastal upwelling upon the waters of Grays Harbor, because no studies have been specifically conducted to permit the tracing of parcels of oceanic water into Grays Harbor. Pearson and Holt (1960) showed that upwelled water did enter the harbor on flood tide. Presumably, the effects of this water on the dissolved oxygen in Grays Harbor will diminish as it moves landward, is subjected to reaeration, and mixes with water from within the estuary.

On several occasions, the lowest DO observed by Pearson and Gotaas (1950 to 1955) was found in upwelled water in the Entrance Reach. This occurred even when the pulp mill BOD was much larger than today.

In an effort to quantify the effect of coastal upwelling on Grays Harbor, Callaway (1971) used a simple steady state mathematical model.

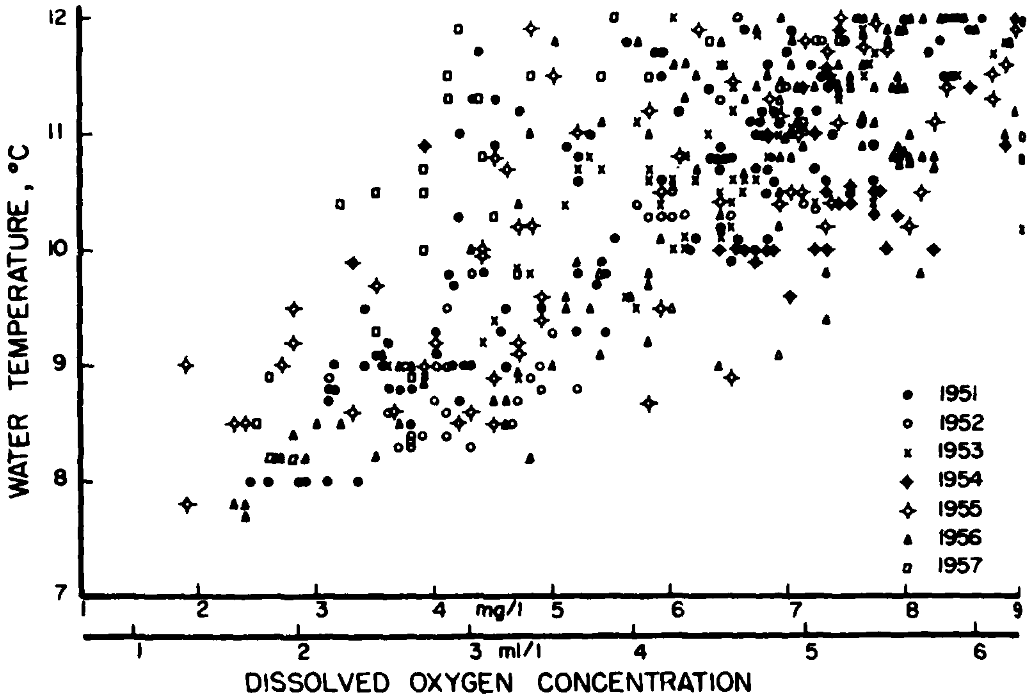


Figure 3-1. Relationship of temperature and oxygen in the oceanic source water at Entrance Reach (From Pearson and Holt, 1960)

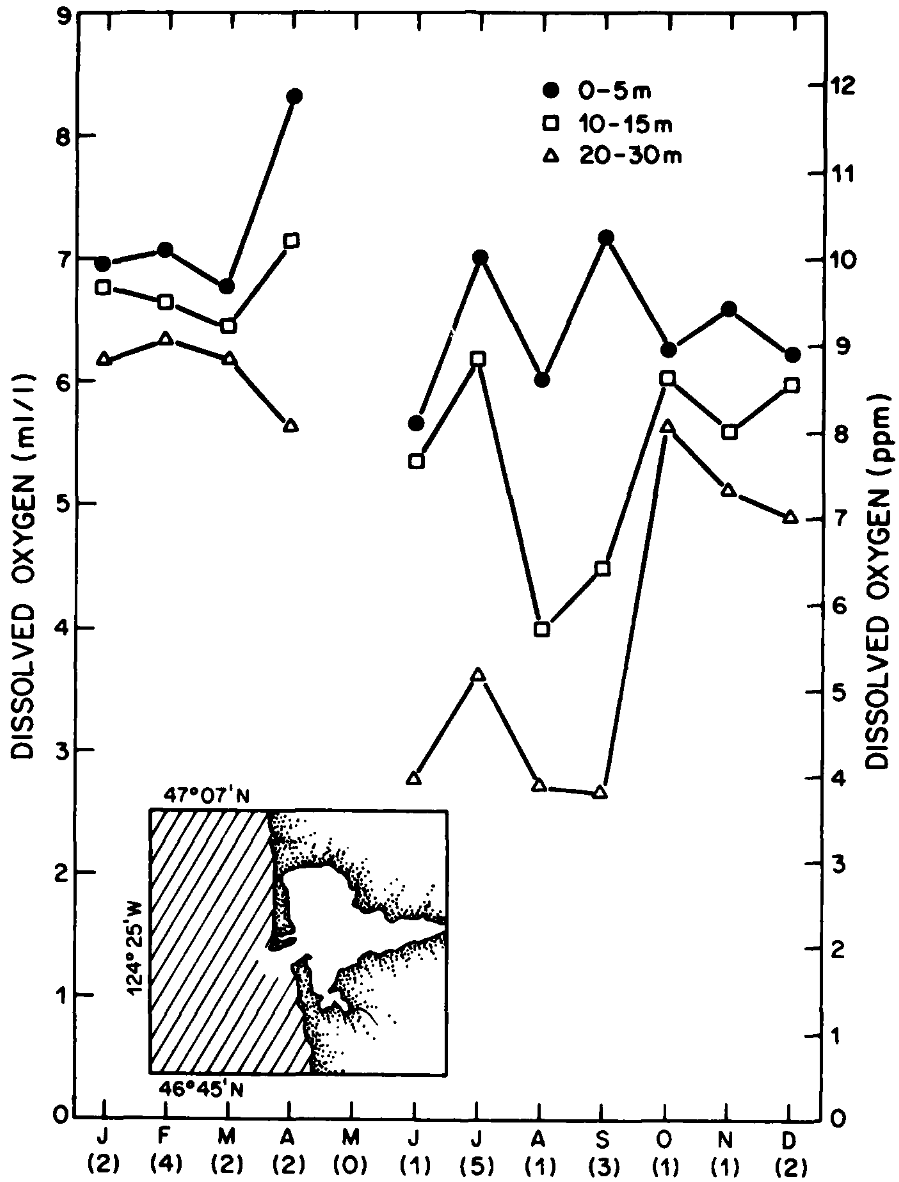
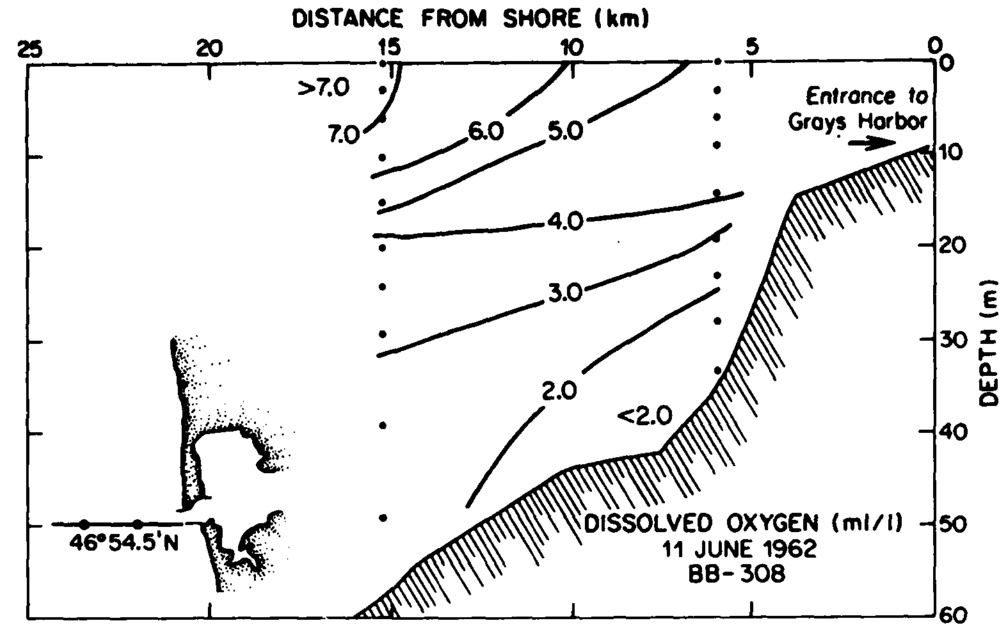


Figure 3-2. Monthly averages of dissolved oxygen offshore of Grays Harbor



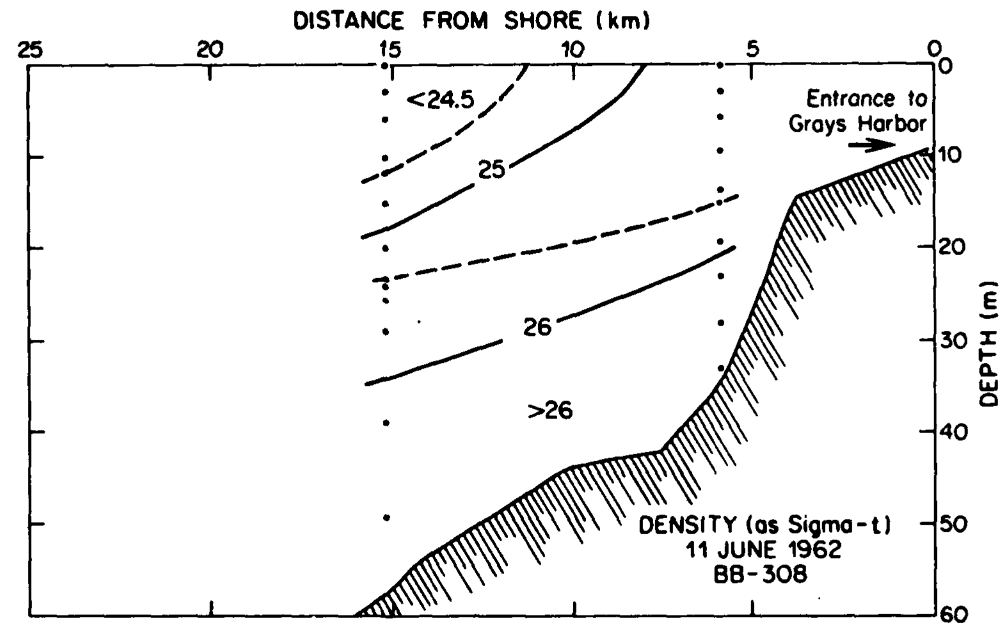


Figure 3-3. Offshore dissolved oxygen and density profiles for 11 June 1962

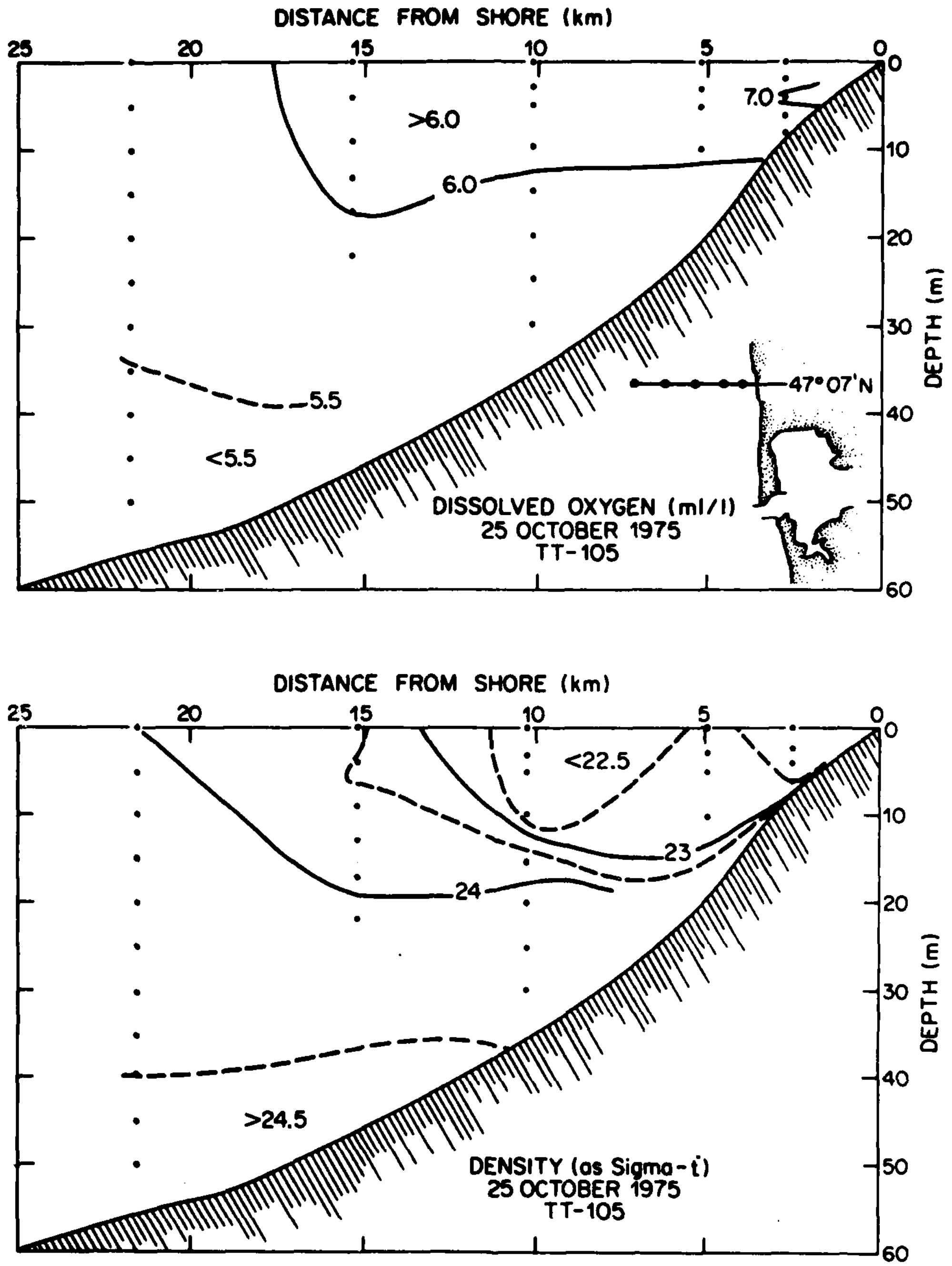


Figure 3-4. Offshore dissolved oxygen and density profiles for 25 October 1975

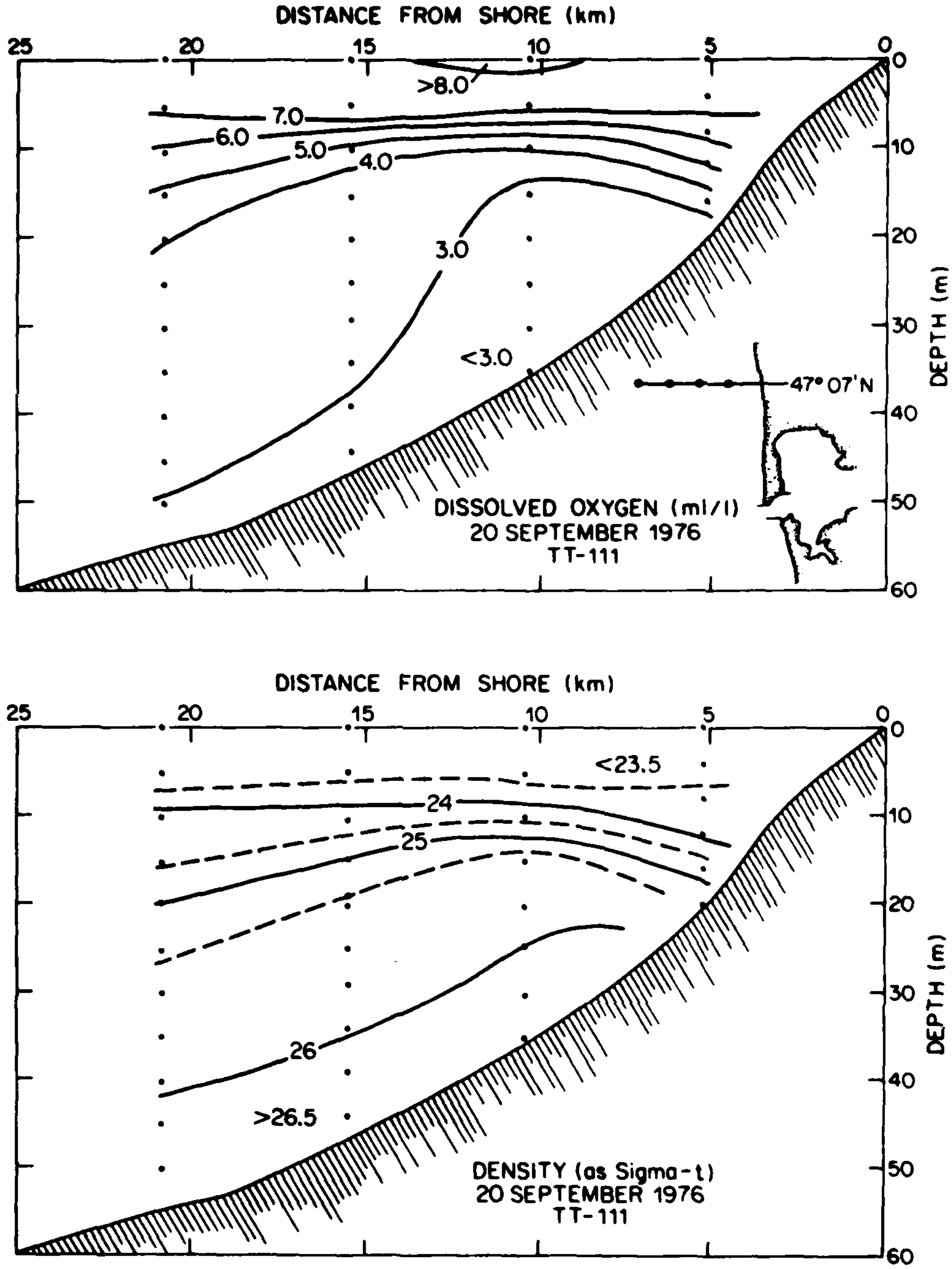


Figure 3-5. Offshore dissolved oxygen and density profiles for 20 September 1976

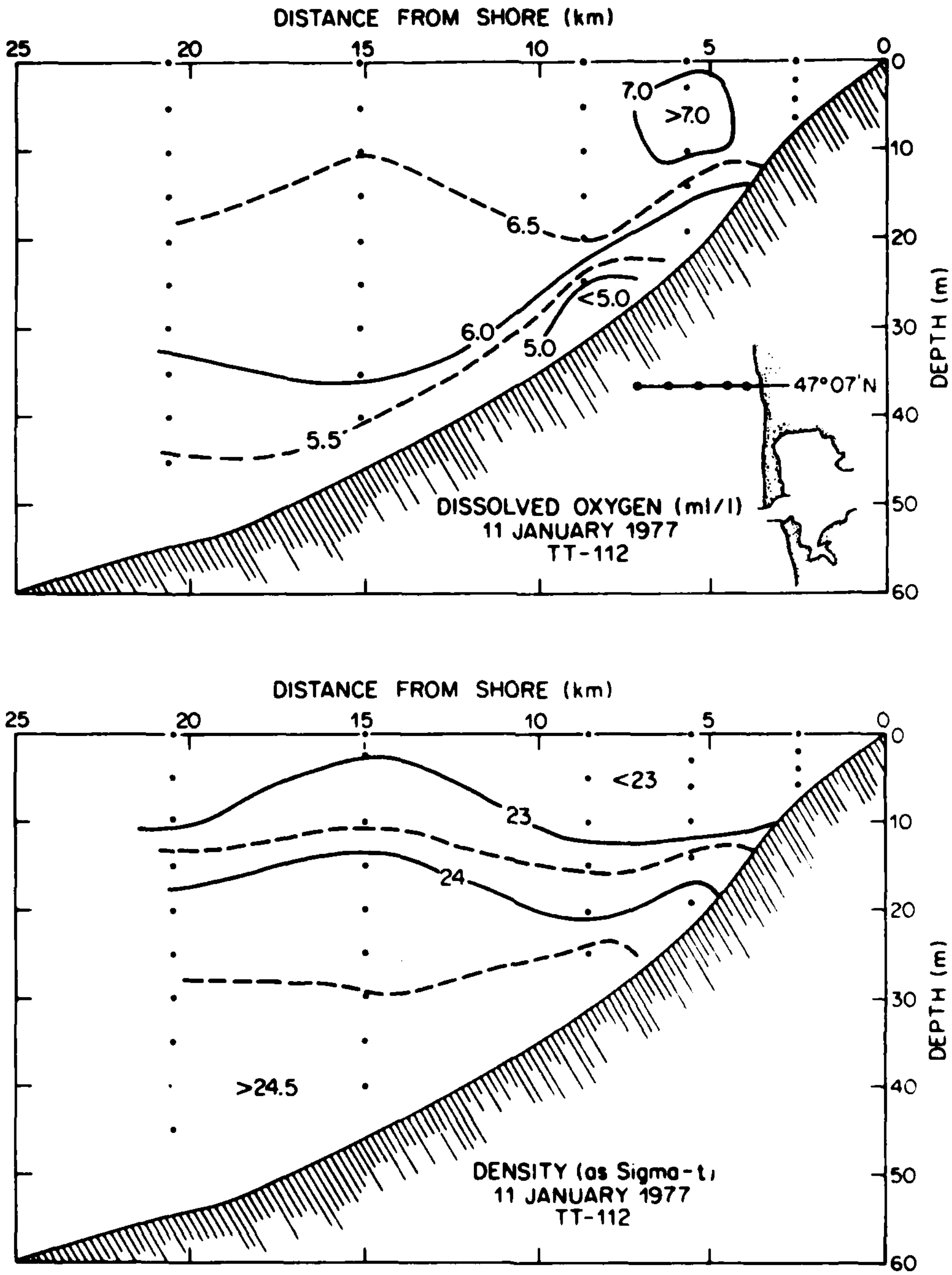


Figure 3-6. Offshore dissolved oxygen and density profiles for 11 January 1977

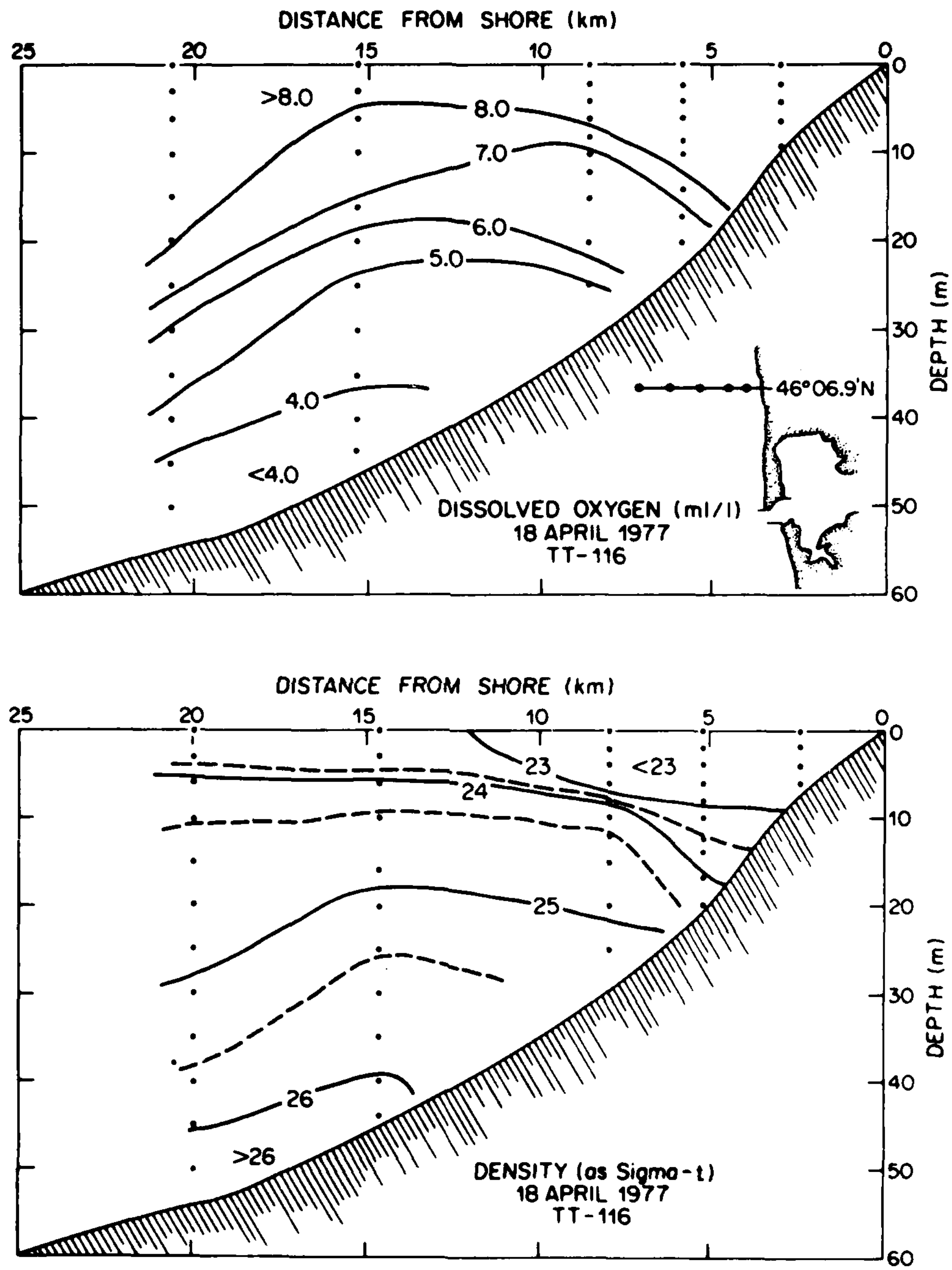


Figure 3-7. Offshore dissolved oxygen and density profiles for 18 April 1977

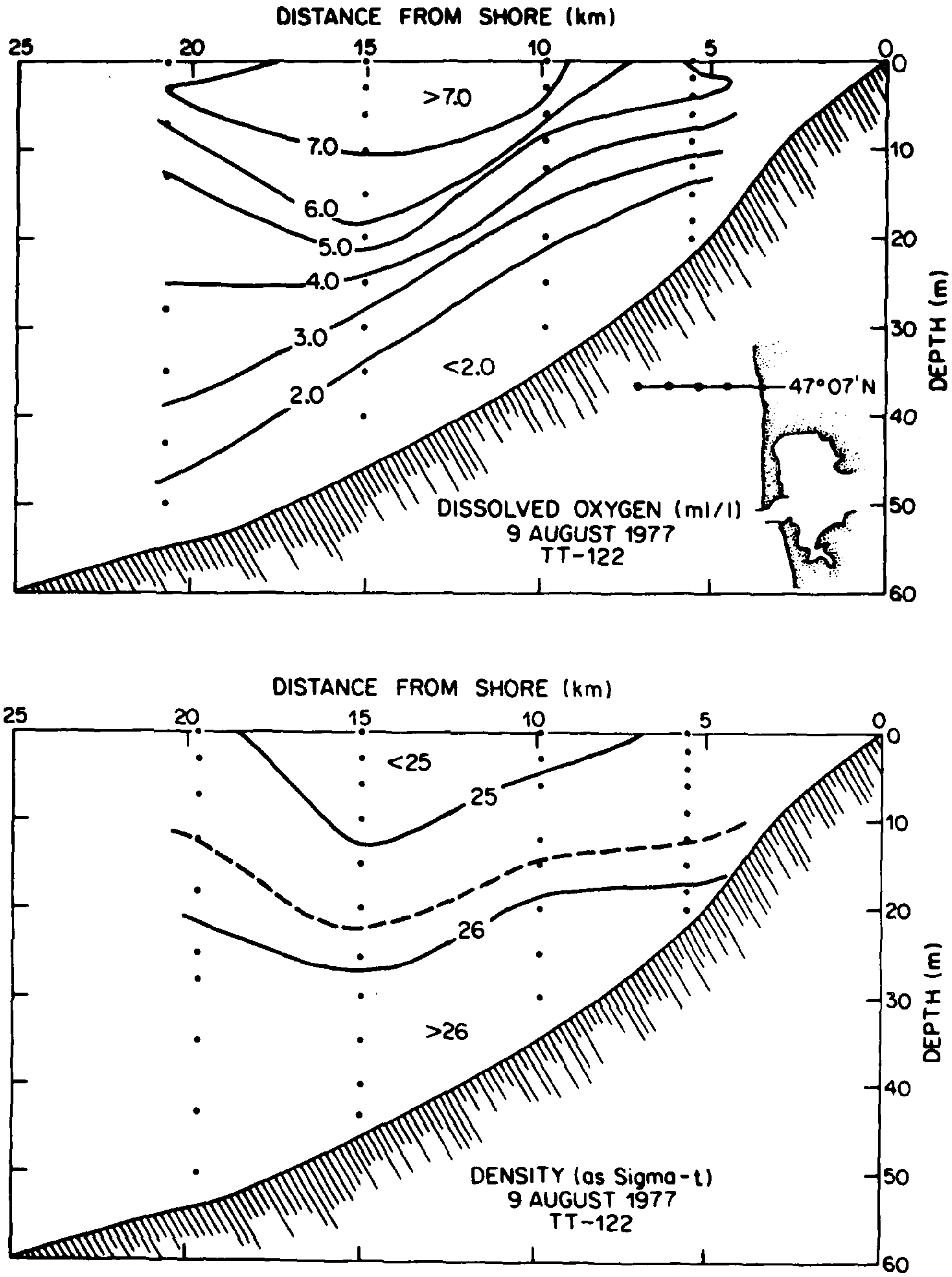


Figure 3-8. Offshore dissolved oxygen and density profiles for 9 August 1977

Callaway introduced upwelling at the ocean end of the model as an oxygen deficit subject only to reaeration. Using reaeration rates of 15 % and 30 % per day, he calculated the impacts of an initial oxygen deficit of 5.5 mg/l on Grays Harbor when the river discharge was set at only 700 cfs. With a reaeration rate of 15 % per day, Callaway showed a diminishing oxygen deficit from the mouth to 18 nautical miles upstream or about to Cosmopolis. He superimposed this deficit on an oxygen deficit given by Eriksen and Townsend (1940) and noted that

> "interpretation of field data extending only eight nautical miles upstream would attribute the entire oxygen sag (off Aberdeen) to the BOD sources located in the middle of the estuary if the possibility of an upwelling effect was not recognized."

Nautical mile 8 is just seaward of Point New or the approximate western boundary of the usual sampling programs conducted since 1965.

3.4 *Tidal Effects*

Tidal action affects water characteristics within an estuary. At a given location, water characteristics are observed to change with tidal periodicity. Bulk movement of the water due to tidal action may be observed by comparing water properties along the major axis of the estuary observed at high tide and again on the following low tide. Similarly, comparison of a low tide profile with the profile on the following high tide may be made. The displacement along the major axis of the same value of a property will provide an indication of tidal excursion.

To illustrate this displacement, water column averaged salinity and DO values for a spring tide and a neap tide were plotted from data provided by Weyerhaeuser (1957-1969). On a spring tide with a range of 11.2 feet and going from low to high tide (Fig. 3-9), the DO near Cosmopolis (Station 44) changed from 8 ppm on the low tide to 4 ppm on the high . Corresponding salinities were 0.5 parts per thousand (‰) and 8 ‰, respectively. But at the west end of Moon Island (Station 54), the lowest DO (3.3 ppm) occurred at low tide while the highest DO (6.8 ppm) occurred on high tide. Corresponding salinities were 14‰ and 19‰.

Similar information for a neap tide are illustrated in Figure 3-10. Here the tide changed from high to low and the range was only 3.2 feet. On the neap tide, the range of change in DO was less, as was the excursion distance. River flows in both cases were low.

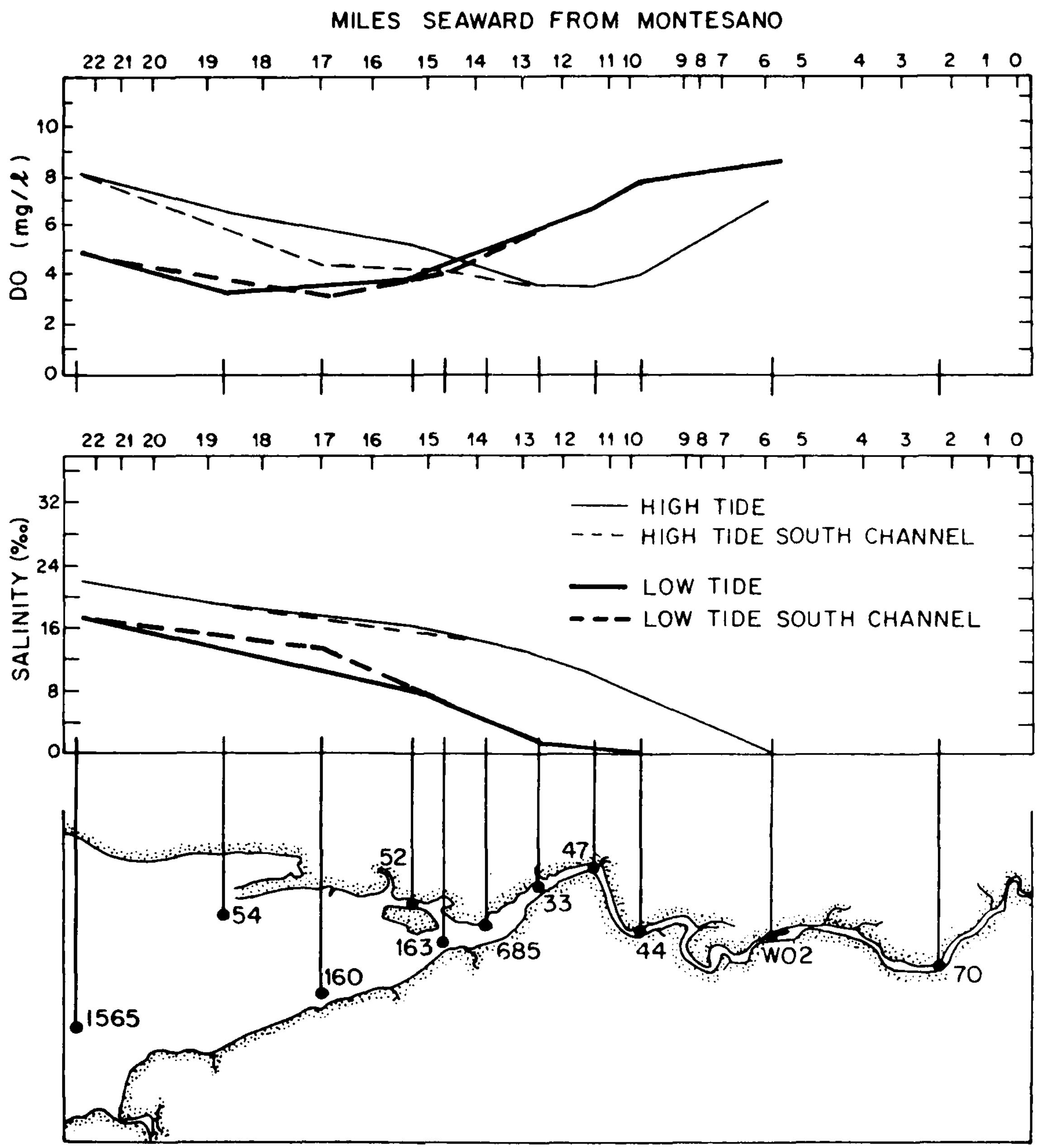


Figure 3-9. Longitudinal profiles of averaged salinity and dissolved oxygen for low tide (-1.3 ft) followed by high tide (8.6 ft) on 23 June 1966. River flow = 1733 cfs.

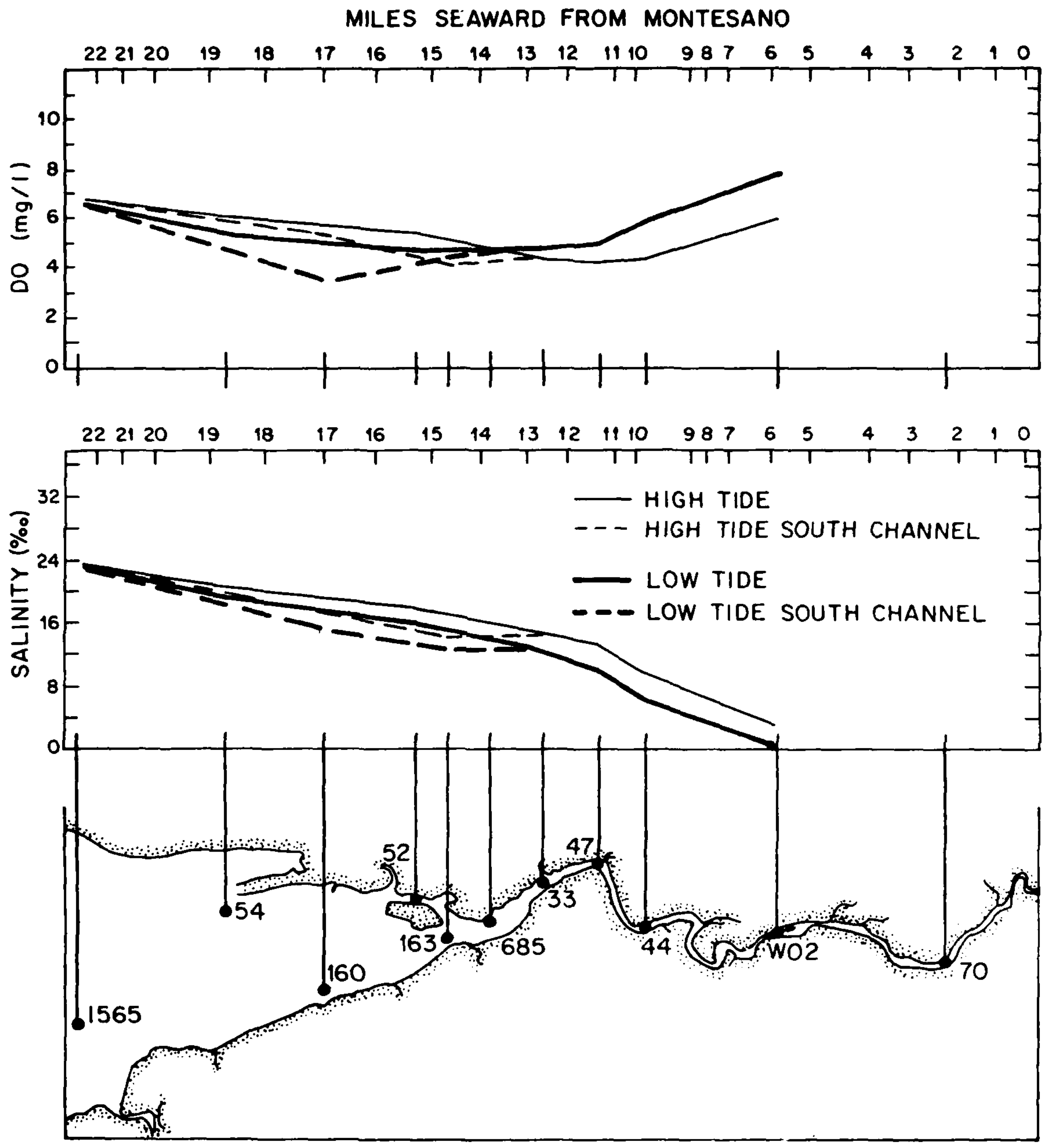


Figure 3-10. Longitudinal profiles of averaged salinity and dissolved oxygen for high tide (6.6 ft) followed by low tide (3.4 ft) on 14 July 1966. River flow = 2417 cfs.

The DO values presented in Figures 3-9 and 3-10 are not representative of today's conditions because they were obtained in 1966. Since then both industrial and domestic wastes have had most of their biological oxygen demand (BOD) removed by more advanced methods of treatment. However, the salinity values are representative of today's conditions because salinity is a conservative property not affected by biological or chemical processes.

These figures also illustrate the depression in DO commonly referred to as the "DO sag." This DO depression is not stationary but moves with the water, downstream on an ebb tide and upstream on a flood. The nodal point of this movement is near Cow Point (station 685). Tidal periodicity in water properties is evident at Cow Point when samples were obtained on a short term basis.

Short term variability of the water properties is illustrated in Figures 3-11 and 3-12. The data used to prepare Figure 3-11 (Moon Island Reach) are old (29 August 1938) but do show the strong tidal periodicity that can occur over a tidal day (24.85 hours). The data shown in Figure 3-12 are from Cow Point Reach and were taken on 20 July 1970. They also show tidal periodicity even though only one-half tidal day is represented.

3.5 *Wind Effects*

Strong winds blowing over an estuary will cause a breakdown of density stratification in the water column. Stratification is more pronounced in winter when river flow is high. Strong winds are also more frequent in winter. As the winds blow over the water surface, mixing will take place, first erroding the surface layer and eventually mixing the whole water column. At such times, the water column may become homogeneous. When the wind subsides, stratification will be reestablished. Because of the nature of the sampling programs in Grays Harbor, data were seldom obtained during periods of strong winds.

3.6 *Seasonal and Monthly Variations of Water Properties*

Variations by season in salinity and temperature for four stations (Chehalis River, Cow Point, Rennie Island, and Moon Island) are presented in Figures 3-13 through 3-16 as bar graphs. Temperature data only for North Bay is shown in Figure 3-17. The data for each bar were averaged by season for selected intervals of river flow and by high or low tide within these river flow intervals. The number of samples available to calculate each average is indicated at the top of each bar and the river flow

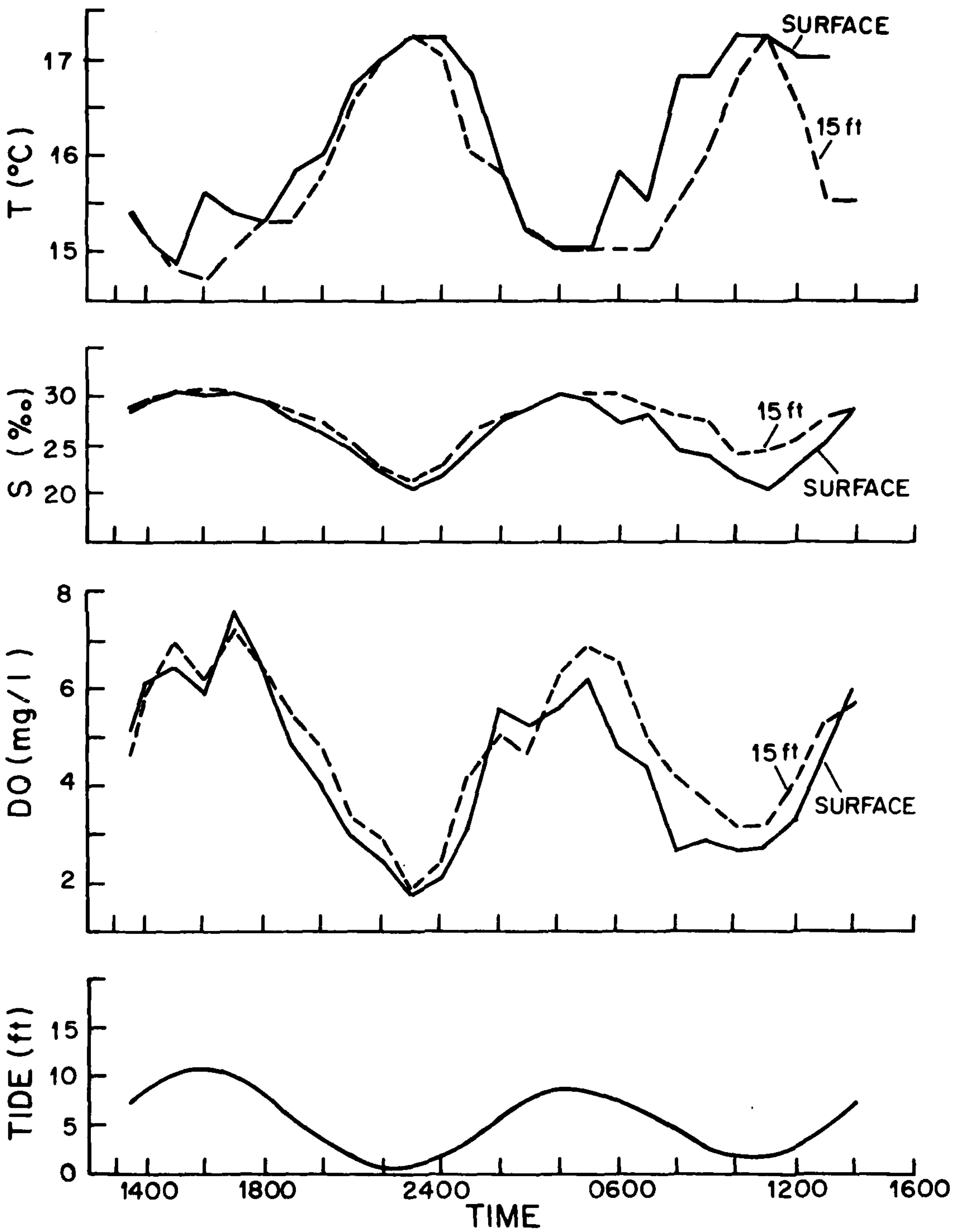


Figure 3-11. Temperature, salinity, dissolved oxygen and tide height for Moon Island Reach on 29 August 1938. River flow = 642 cfs. Note that the lowest DO occurs at this station at low tide.

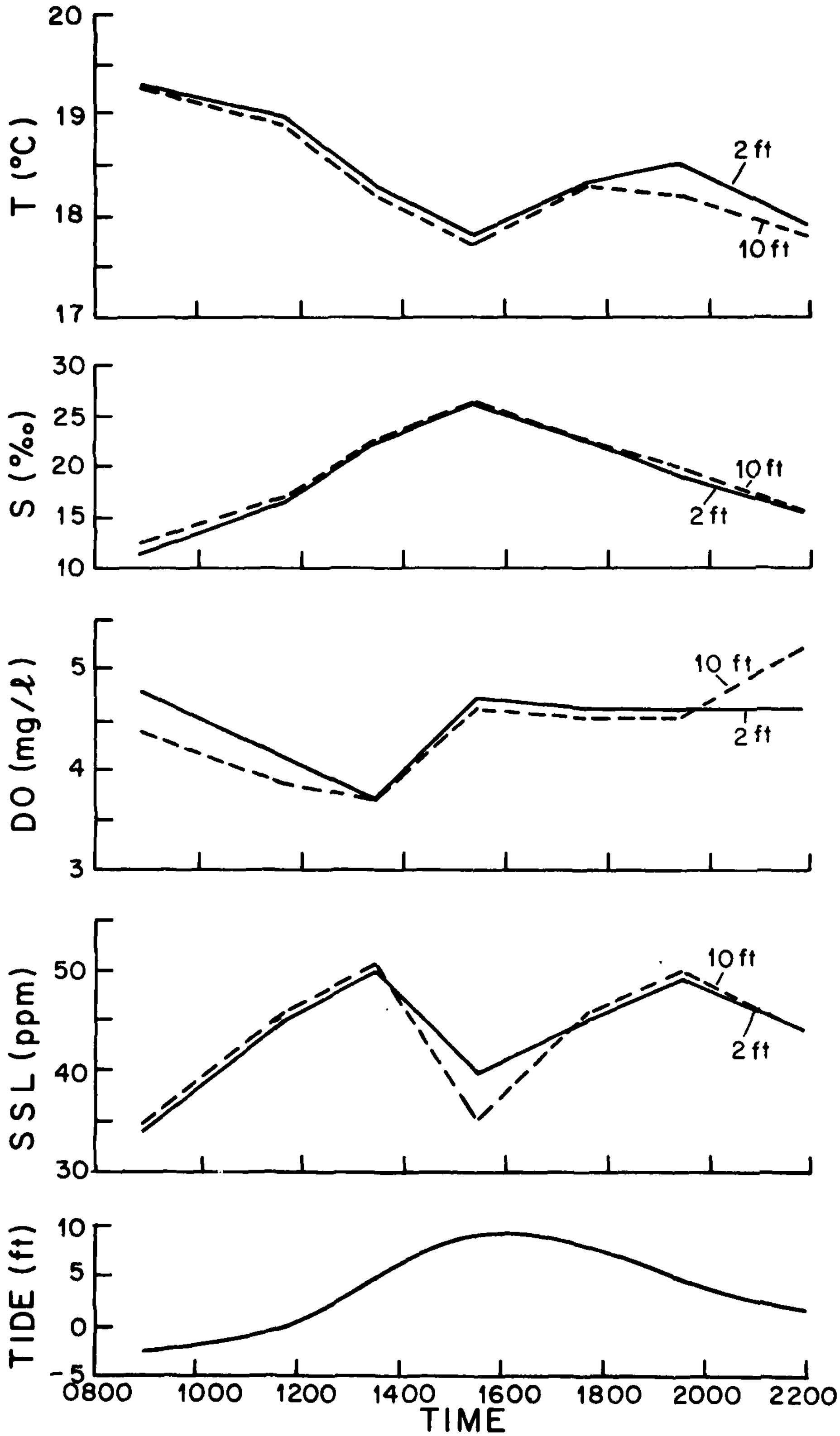


Figure 3-12. Temperature, salinity, dissolved oxygen, spent sulfite liquor and tide for Cow Point Reach on 20 July 1970. River flow = 648 cfs. Note that the lowest DO occurs at this station at mid-tide.

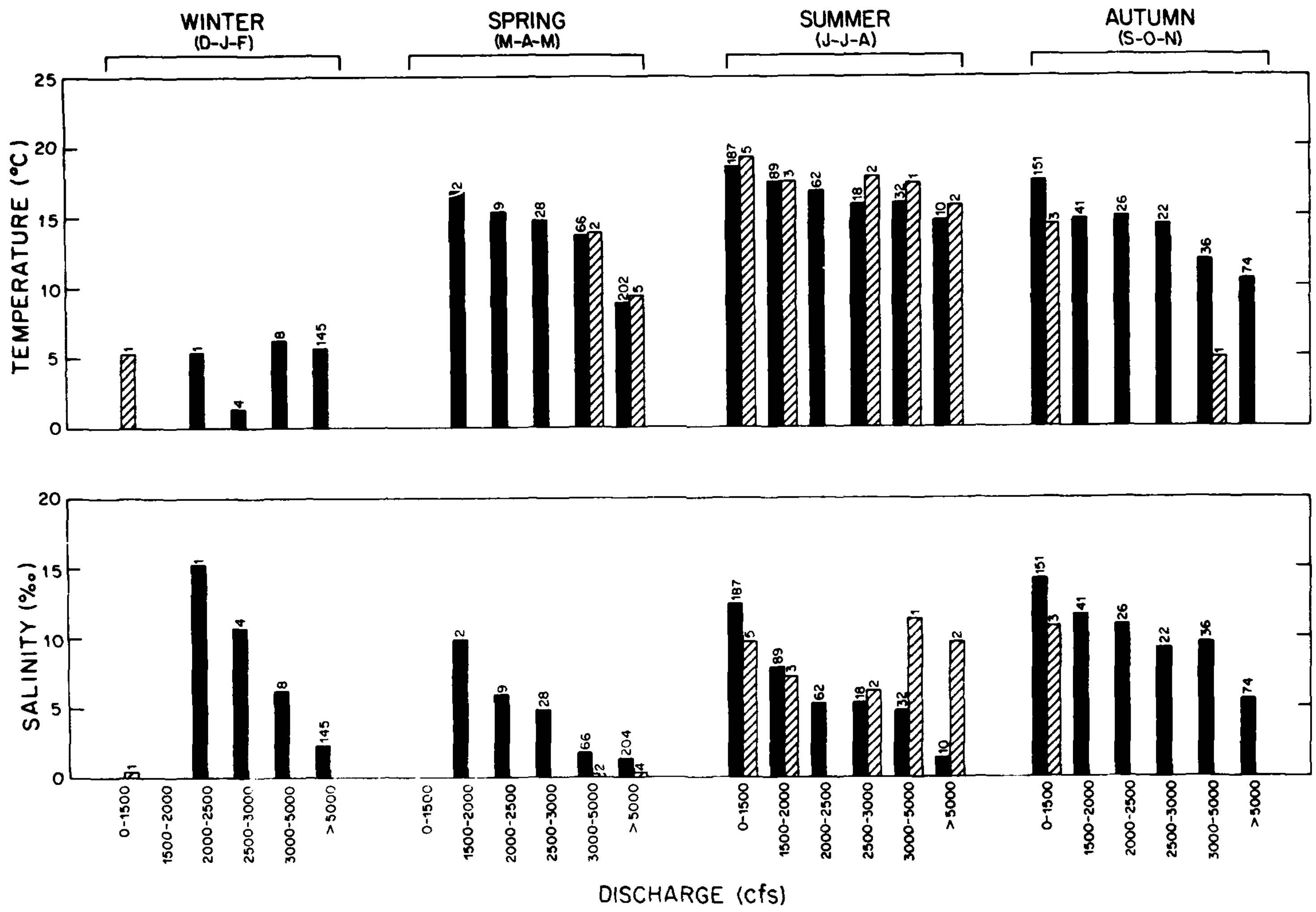


Figure 3-13. Variations in temperature and salinity by season, tide and river flow for stations in the Chehalis River near Cosmopolis. Solid bars are high tide averages and patterned bars are for low tide. The number at the top of each bar gives the number of observations that the average was computed from.

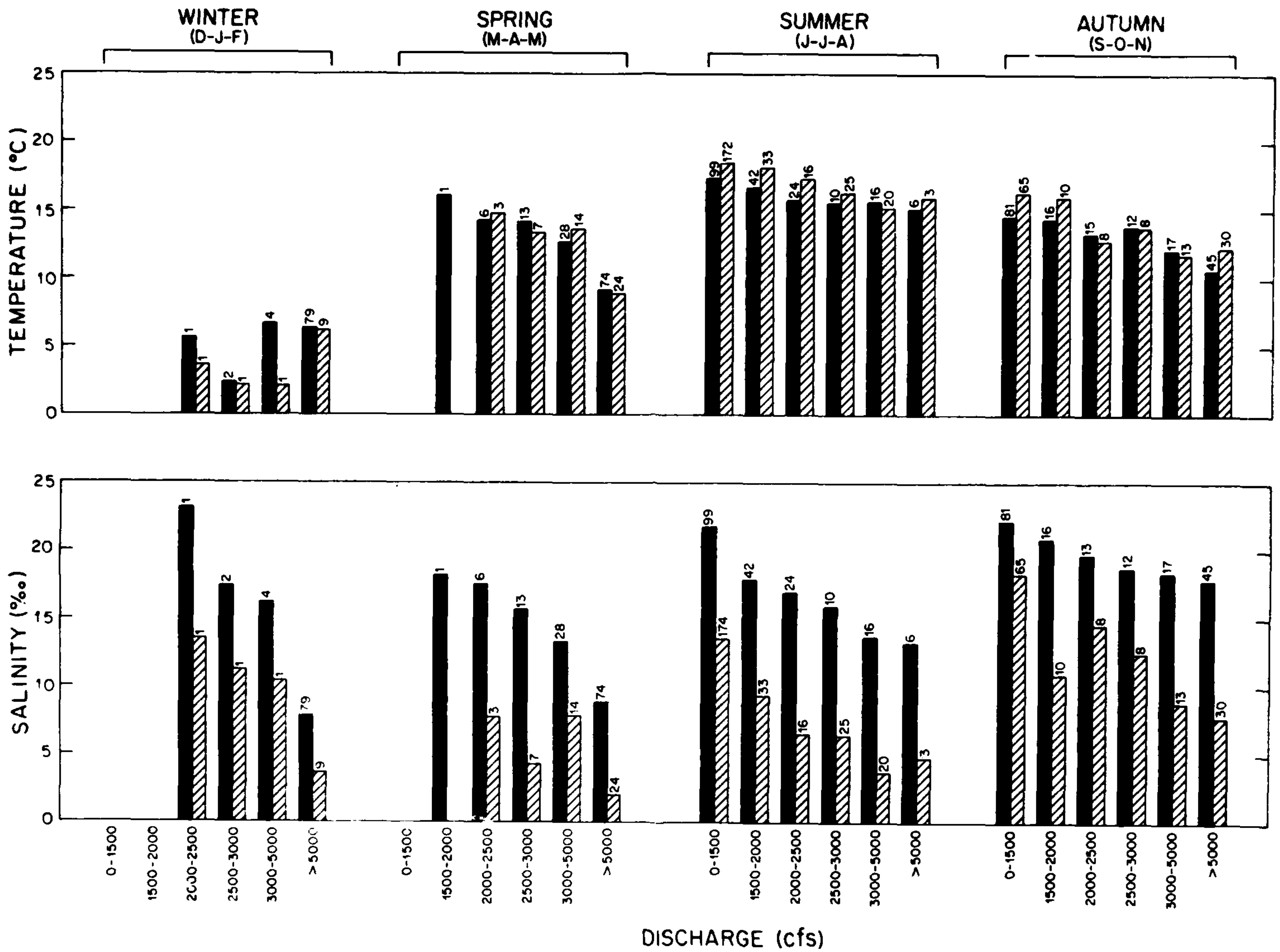


Figure 3-14. Variations in temperature and salinity by season, tide and river flow for stations in Cow Point Reach. Solid bars are high tide averages and patterned bars are for low tide. The number at the top of each bar gives the number of observations that the average was computed from.

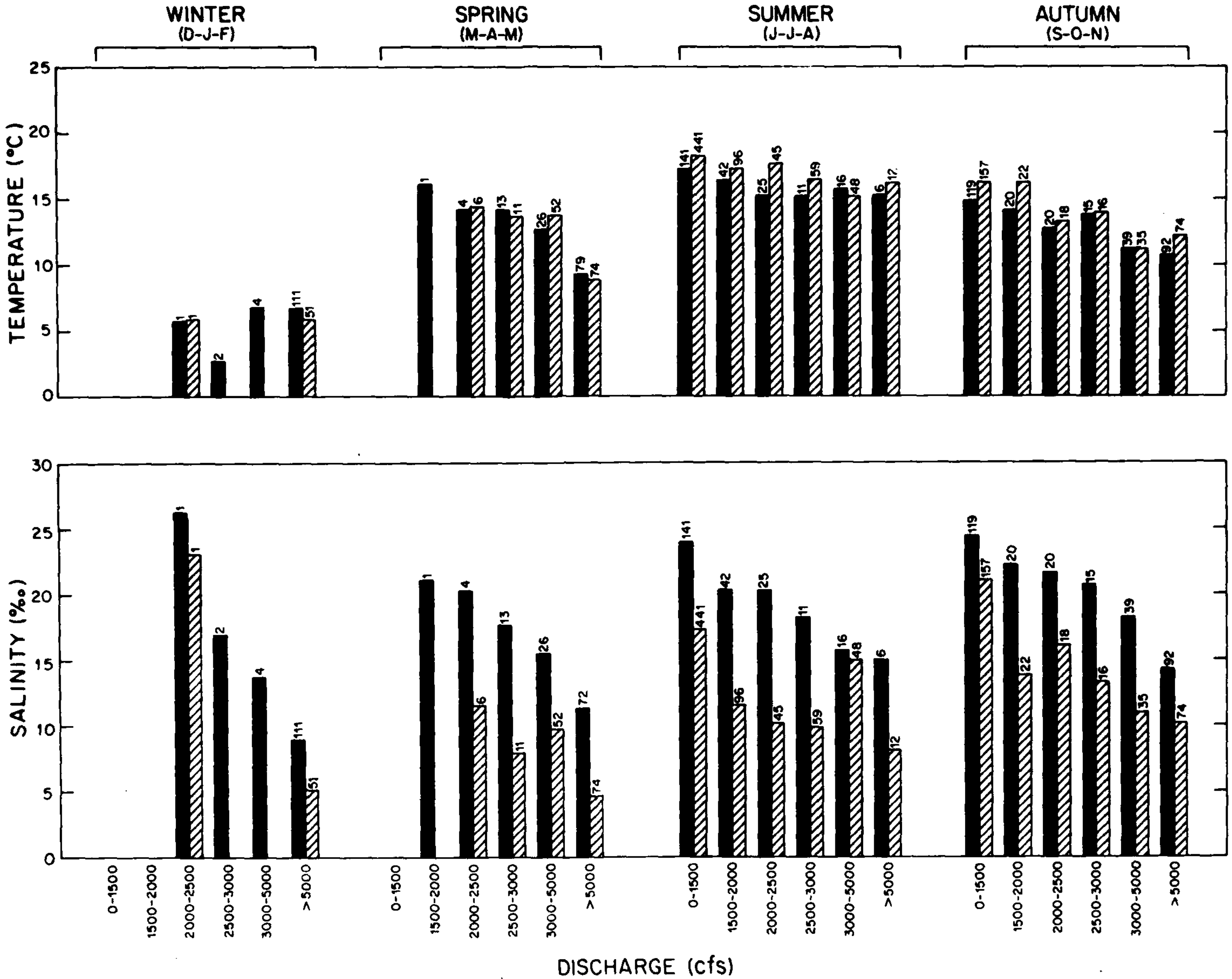


Figure 3-15. Variations in temperature and salinity by season, tide and river flow for Station 52 off Rennie Island. Solid bars are high tide averages and patterned bars are for low tide. The number at the top of each bar gives the number of observations that the average was computed from.

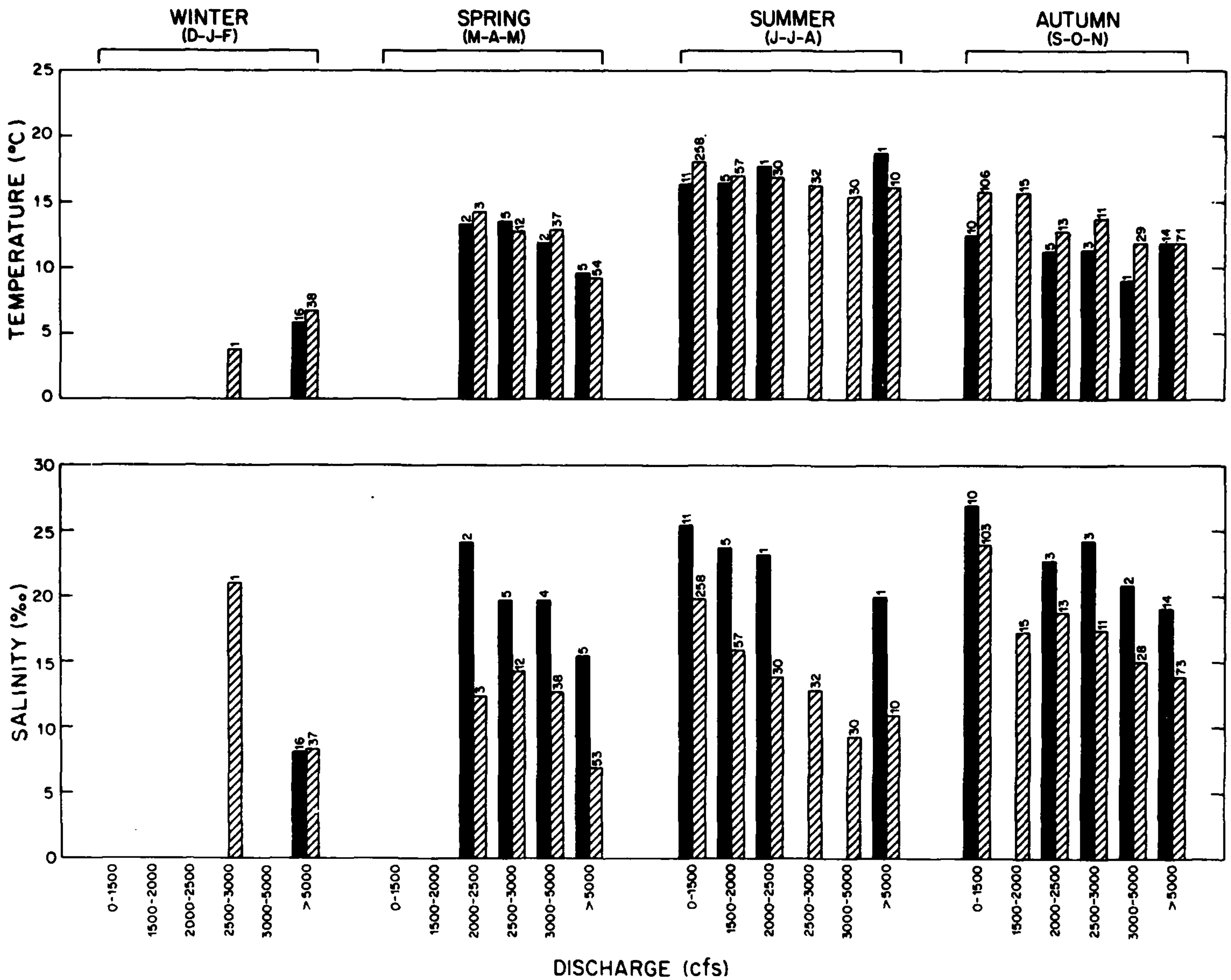


Figure 3-16. Variations in temperature and salinity by season, tide and river flow for stations in Moon Island Reach. Solid bars are high tide averages and patterned bars are for low tide. The number at the top of each bar gives the number of observations that the average was computed from.

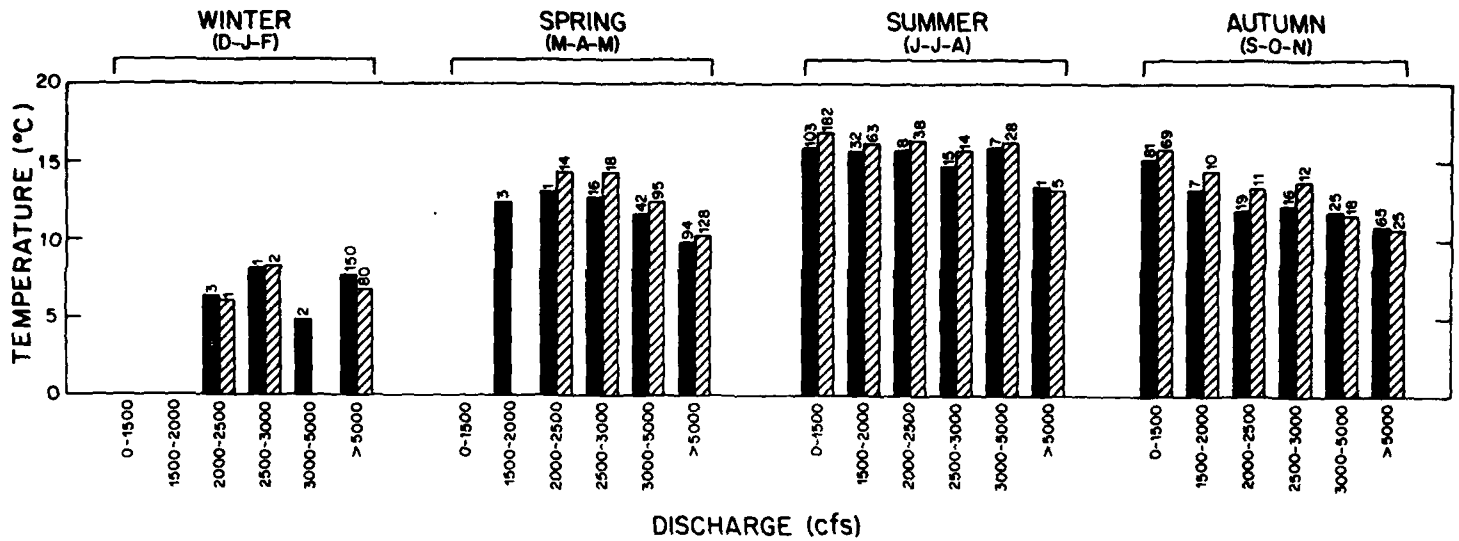


Figure 3-17. Variations in temperature by season, tide and river flow for Station HUT in North Bay. Solid bars are high tide averages and patterned bars are for low tide. The number at the top of each bar gives the number of observations that the average was computed from.

interval is specified at the bottom. Solid bars are for high tide samples and the patterned bars are for low tide.

During summer, the average water temperature was above 15°C throughout most of Grays Harbor for all river flows. Average temperatures at low tides and with a river flow of less than 1,500 cfs were highest at the Chehalis River station (19°C) and decreased seaward to North Bay, where the temperature was 16°C. In spring and fall, temperatures were similar under similar tide stage and river flow. Winter temperatures were independent of river flow and varied from 2°C to 6°C for stations in the inner harbor and from 5°C to 8°C in the outer harbor. In general, the waters in Grays Harbor were warmer at the head of the system and cooler at the entrance in summer. Conversely in winter, the warmest waters were found near the entrance. This reflects the cooler temperature of the large amount of fresh water introduced into the system during winter.

In all of Grays Harbor, the salinity is highly variable both in space and time. The salinity bar graphs on Figures 3-13 through 3-16 show the effects of tide stage, river flow, and season. Salinity decreases from the entrance to the head of the estuary and at any given location, the salinity decreases with increasing river flow. Salinity is lower at low tide than at high tide and the difference in salinity between low and high tide (i.e., salinity range) increases from the entrance of Grays Harbor towards Cosmopolis, reflecting the influence of the Chehalis River. The salinity in the water column varies from top to bottom, being higher at the bottom. Variations in the water column are not evident in these figures because data from all depths were averaged together. During fall, the salinity for any combination of river flow and tide stage was consistently higher for all stations than in other seasons, indicating the long term effect of coastal upwelling. Coastal upwelling will gradually increase the salinity of the source water. This coupled with a decrease in river flow will permit the average salinity of Grays Harbor water to increase to a seasonal high in September. As upwelling subsides and river flow increases, the average salinity of the waters in Grays Harbor will decrease. Surface salinities of the source oceanic water off Grays Harbor vary from about 20 ‰ in the winter when the Columbia River plume turns north and hugs the Washington coast to about 33 ‰ in the summer during coastal upwelling.

Monthly means averaged over two year intervals for temperature, salinity, DO and river flow are presented in Figures 3-18 through 3-23 for stations in Chehalis River, Aberdeen Reach East, Cow Point, two stations in Hoquiam Reach (52 and 53), and Moon Island Reach. The river flows indicated for high and low tide are different because only the river data for those days when water samples were collected were used in these averages. Each diagram shows two solid lines which are plus or minus one standard deviation for the specified intervals of years. These figures show the seasonal cycle where temperatures are lowest in winter and highest in summer. The salinity is lowest in February and highest in September. Dissolved oxygen is depressed in July and August when the river flow is reduced. Because of changes in treatment of wastes by industry (see Table 3-2), the DO values for the late 1970's are higher than in previous years.

In order to show more detail in temperature and DO during the critical months of July, August and September, Figures 3-24 through 3-26 were prepared. The data were averaged by two-year intervals from 1965 to 1979. Changes in sampling emphasis from low tide to high tide in 1970 are evident. The DO diagrams (Figs. 3-25 and 3-26) show a definite improvement while the temperature diagram (Fig. 3-24) indicates a slight lowering of mean temperatures which may be related to changes in river flow in the 1970's compared to the 1960's.

Water characteristics at high tide for 1976 at station 52 in Hoquiam Reach are presented in Figures 3-27 through 3-29. Near surface and near bottom values for temperature, salinity, density, DO, oxygen saturation, spent sulfite liquor (SSL), pH, turbidity and river flow are shown. Station 52 is close to the ITT Rayonier pulp mill outflow, so observed levels of SSL are relatively high. The river flow in fall and winter was unusually low because the rainfall during this period was very much below normal, resulting in a near drought. It is apparent in Figure 3-28 that DO and SSL are inversely related. The mill wastes contain significant amounts of material with high BOD, thus reducing the DO at this station. Recent advances in the treatment of pulp mill effluent has dramatically reduced the BOD without removing the component of the effluent measured in the test for SSL. Hence, recent measurements of SSL do not reflect the BOD loading as they once did.

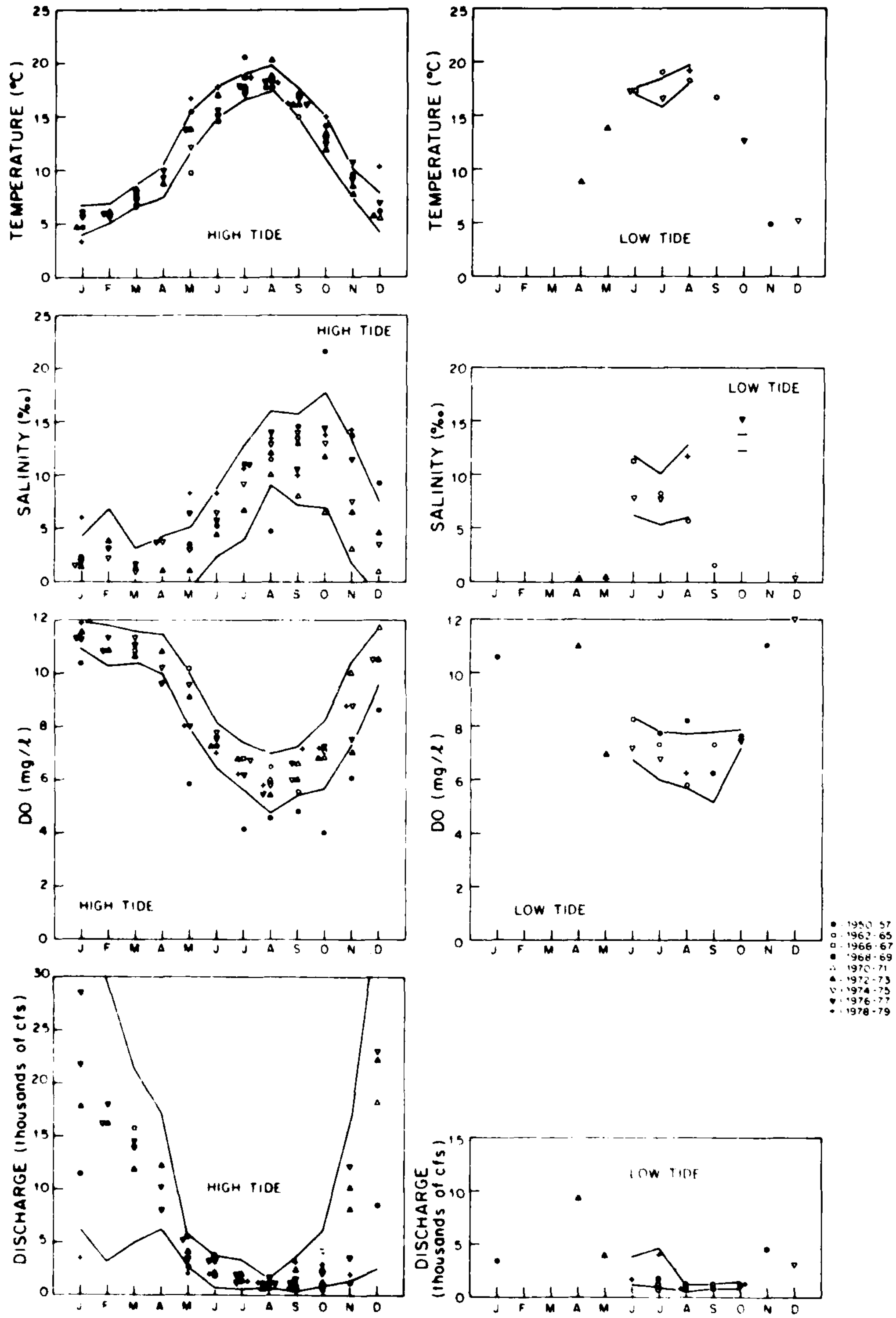


Figure 3-18. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides in the Chehalis River near Cosmopolis. Solid lines are ± 1 standard deviation for data from 1951 to 1979.

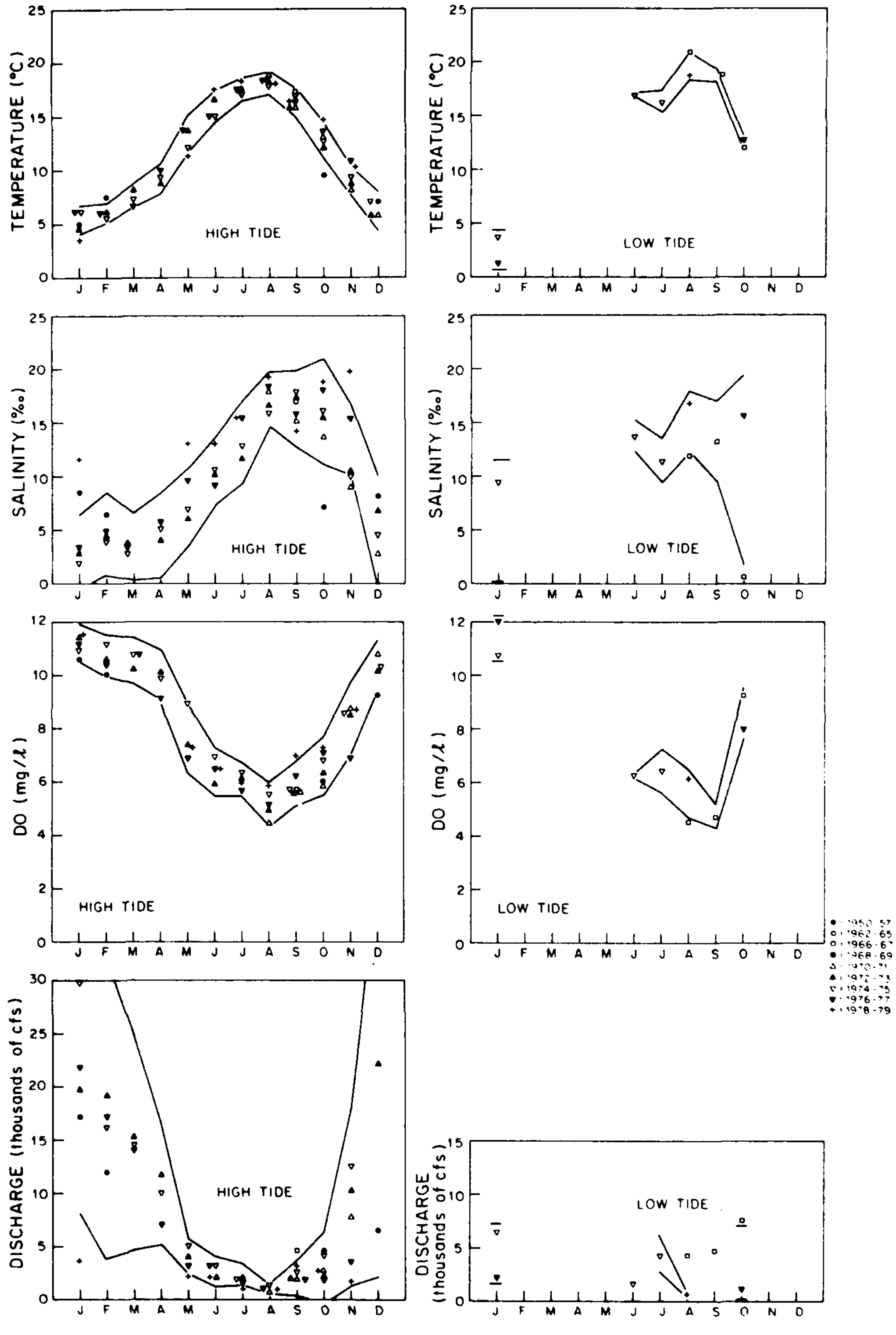


Figure 3-19. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides in the east end of Aberdeen Reach. Solid lines are ± 1 standard deviation for data from 1967 to 1979.

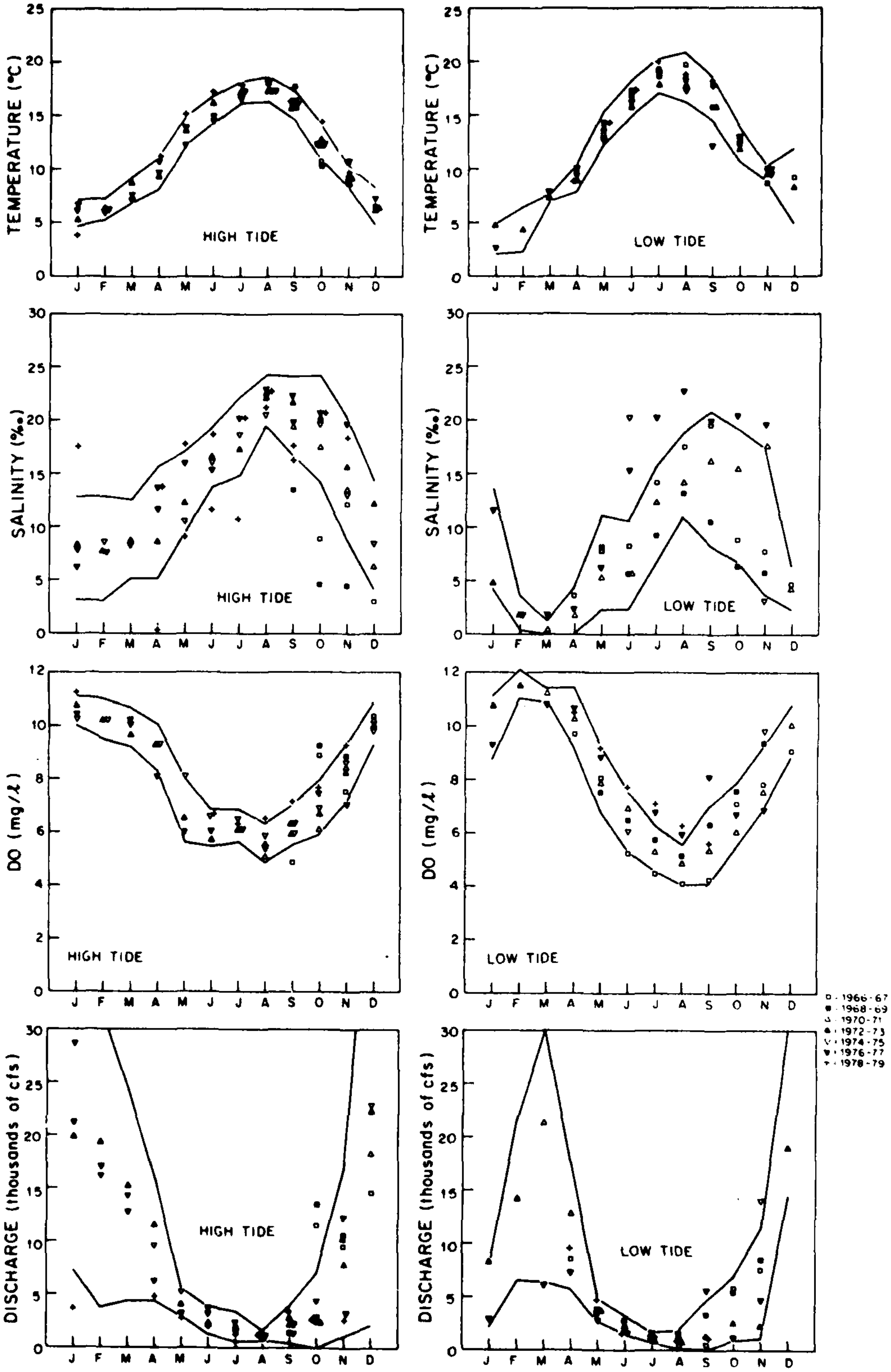


Figure 3-20. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides in Cow Point Reach. Solid lines are ± 1 standard deviation for data from 1966 to 1979.

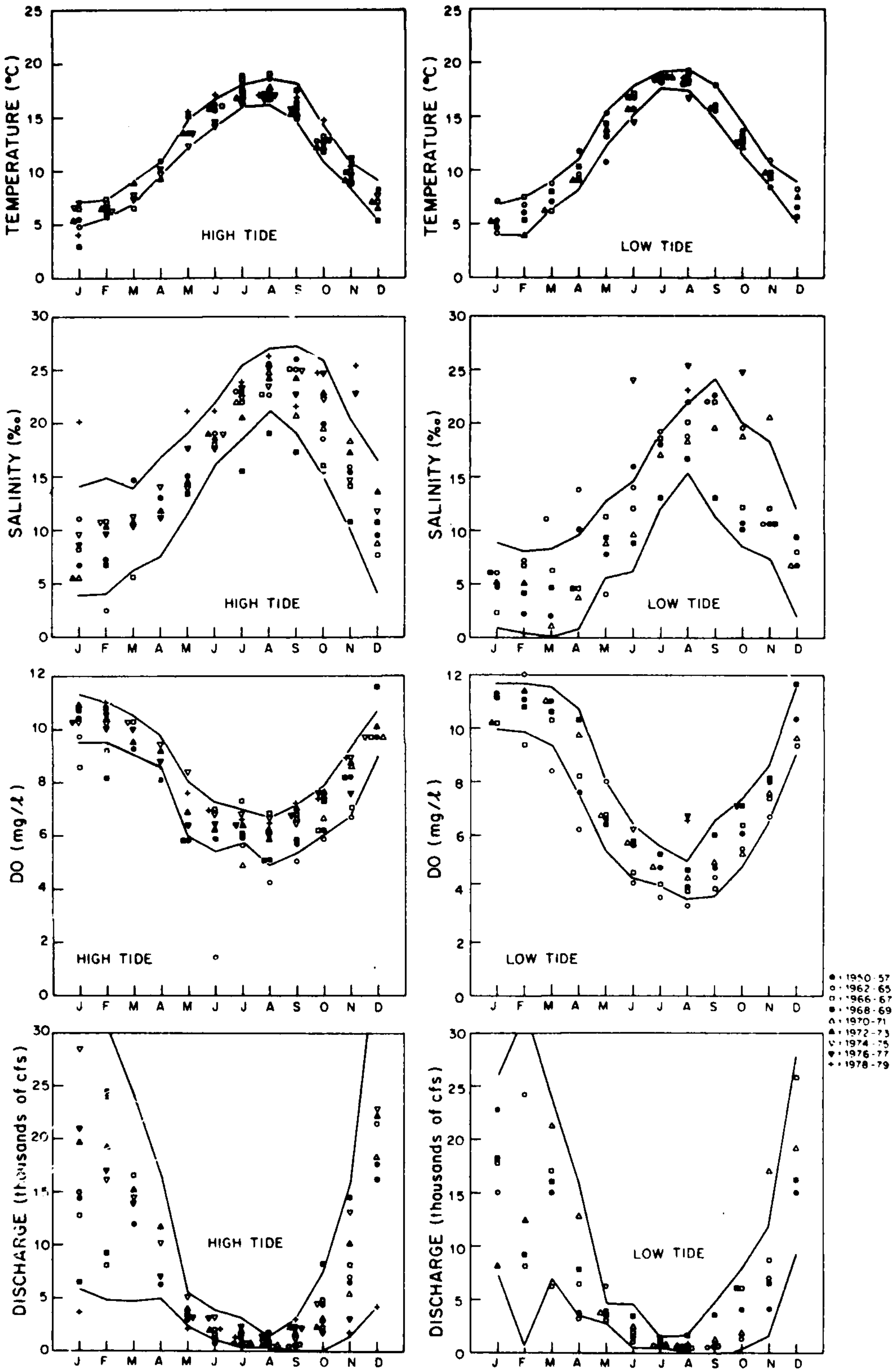


Figure 3-21. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides at Station 52 off Rennie Island. Solid lines are ± 1 standard deviation for data from 1950 to 1979.

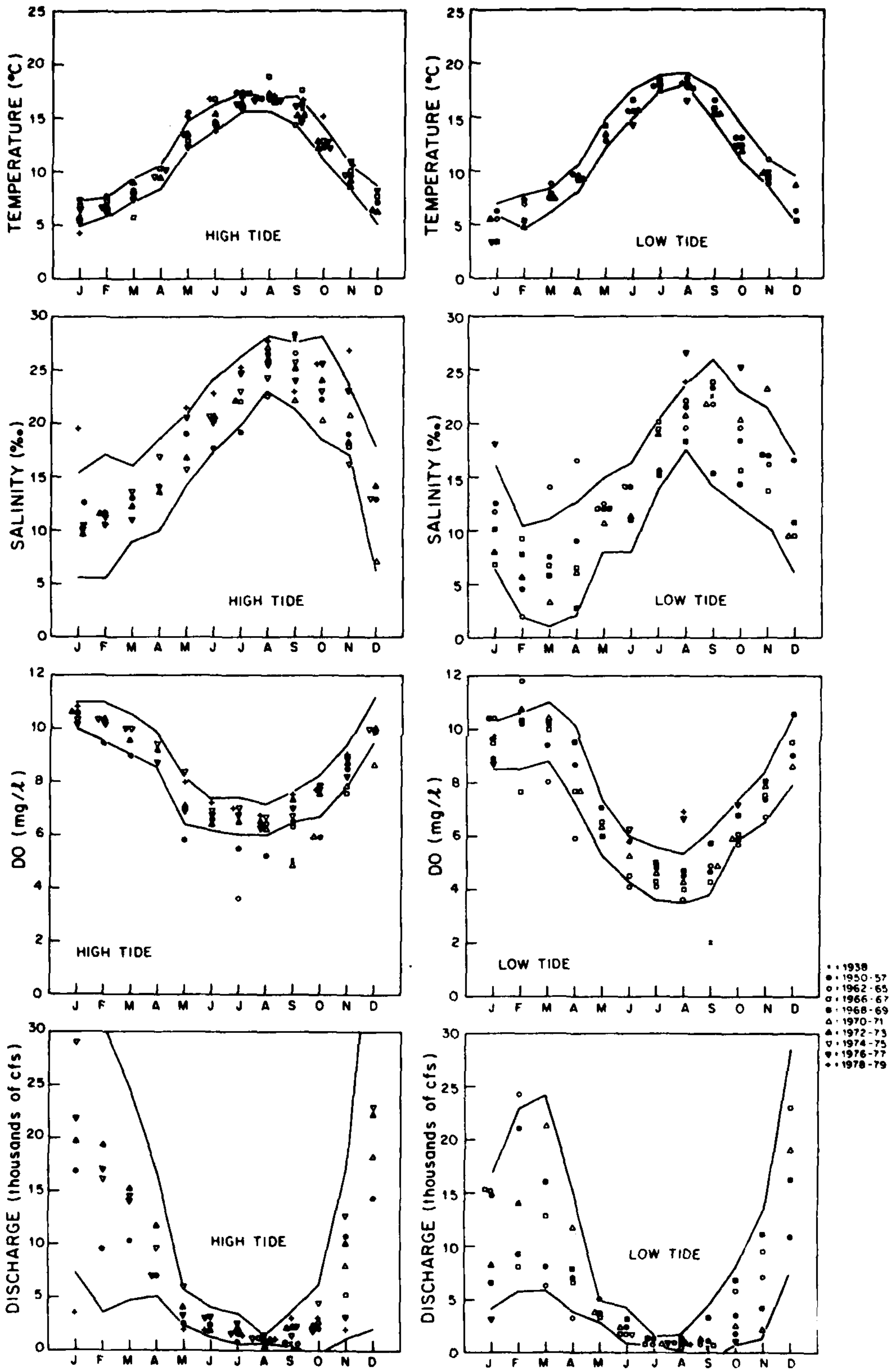


Figure 3-22. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides at Station 53 in Hoquiam Reach. Solid lines are ± 1 standard deviation for data from 1950 to 1979.

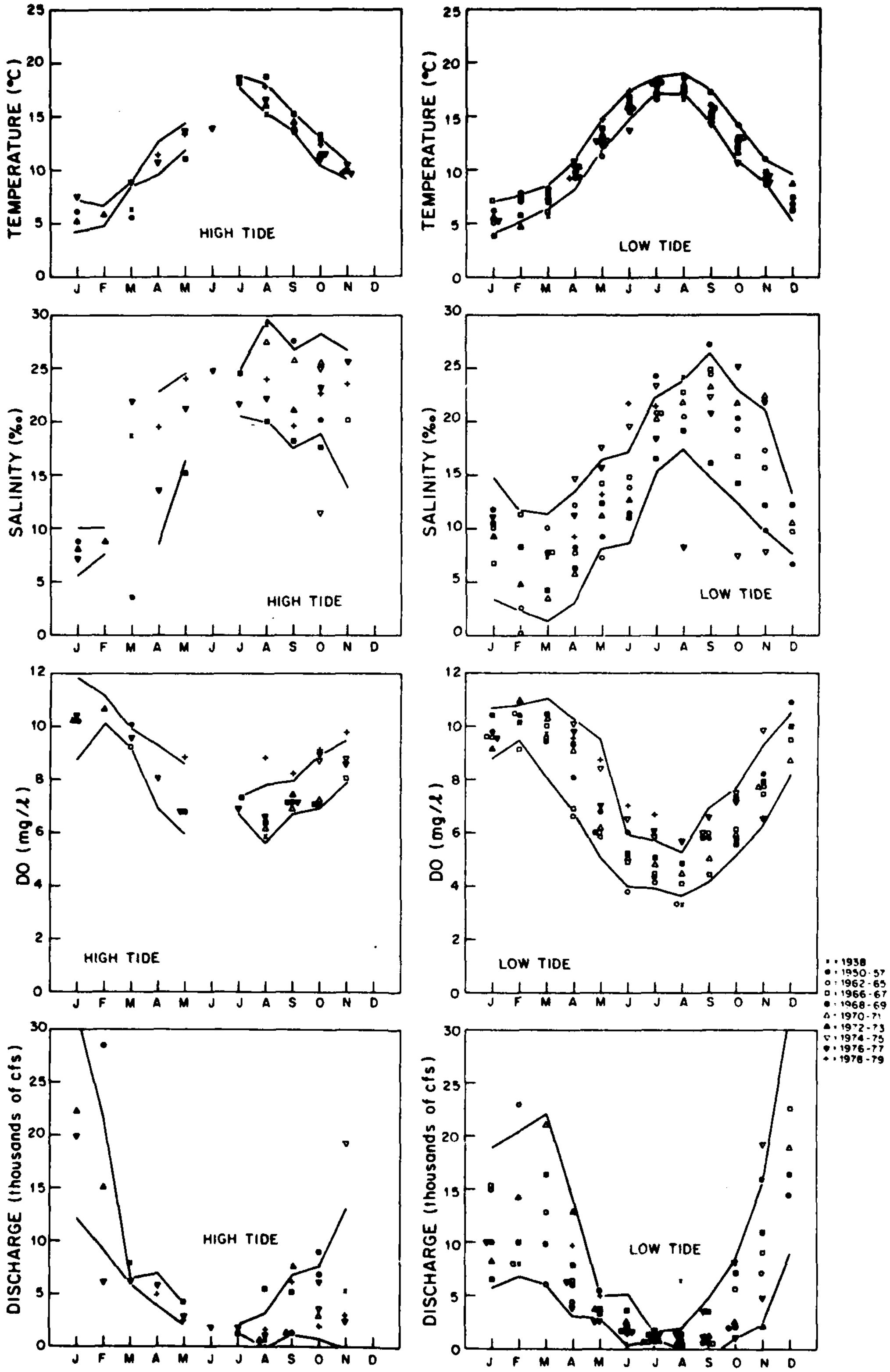


Figure 3-23. Monthly means of temperature, salinity, dissolved oxygen and river discharge for high and low tides in Moon Island Reach. Solid lines are ± 1 standard deviation for data from 1965 to 1979.

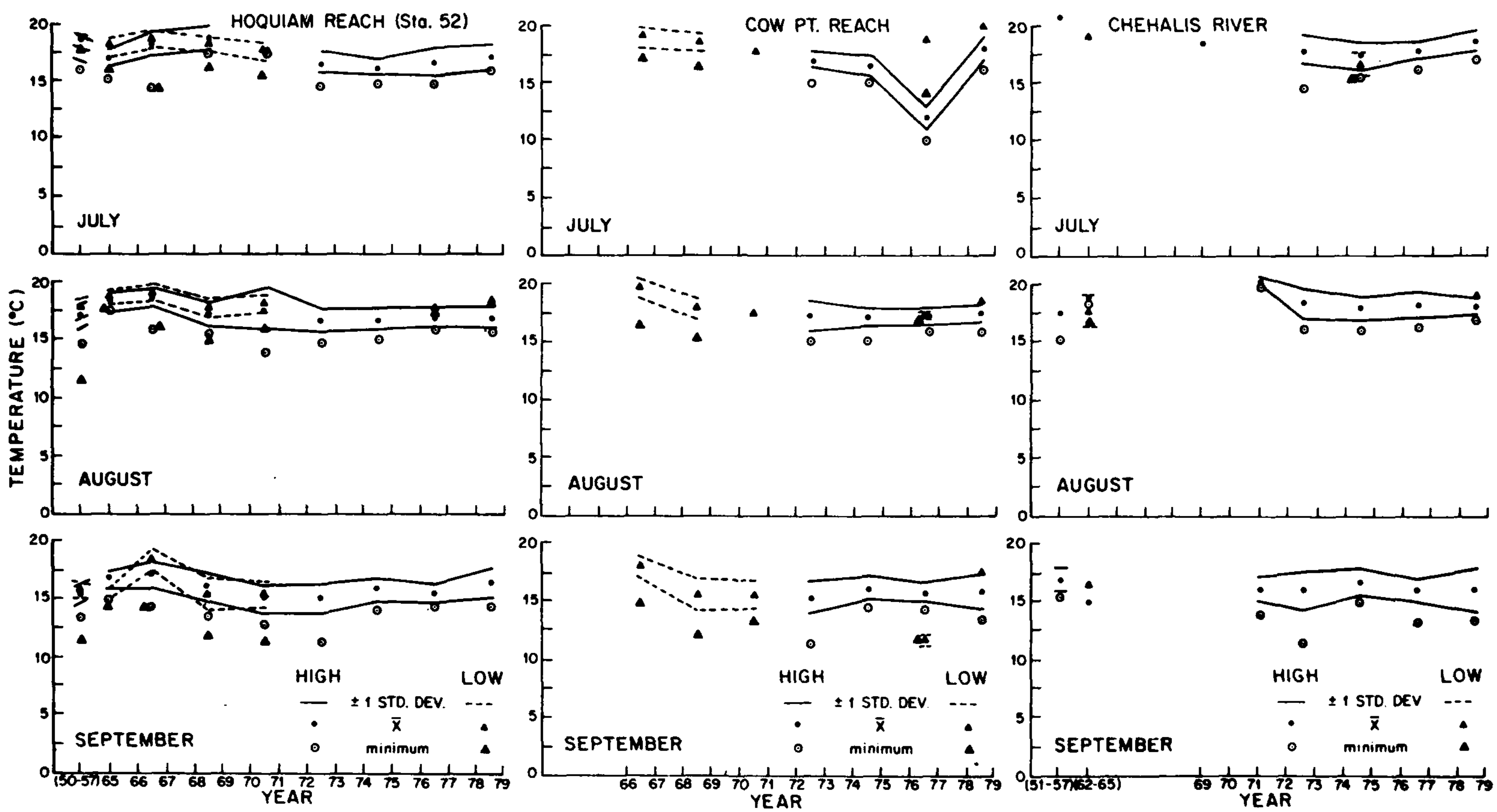


Figure 3-24. Temperature changes during the summer months for Hoquiam Reach, Cow Point Reach, and Chehalis River stations near Cosmopolis. Mean and minimum values, and envelopes of plus or minus one standard deviation are presented for high tide and low tide observations.

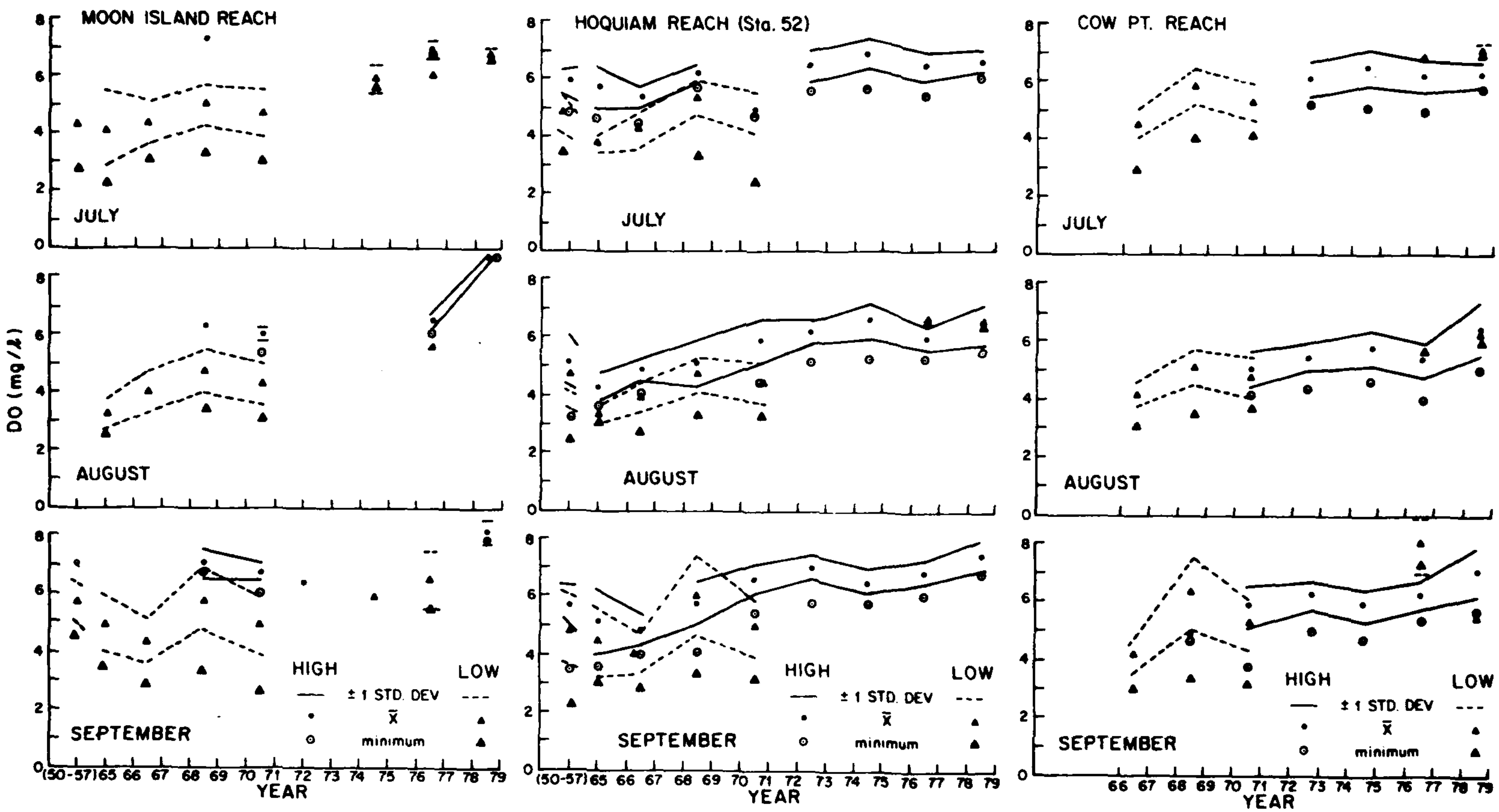


Figure 3-25. Dissolved oxygen changes during the summer months for Moon Island, Hoquiam and Cow Point Reaches. Mean and minimum values, and envelopes of plus or minus one standard deviation are presented for high tide and low tide observations.

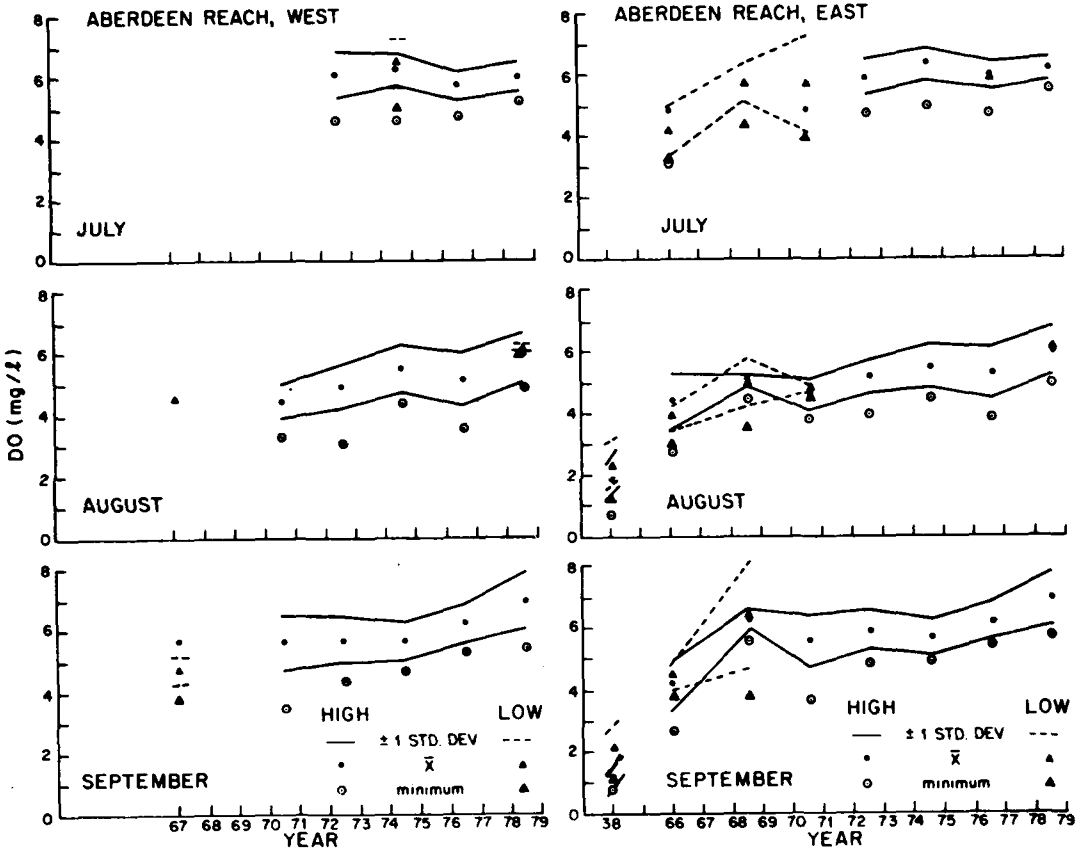


Figure 3-26. Dissolved oxygen changes during the summer months for the west and east portions of Aberdeen Reach. Mean and minimum values, and envelopes of plus or minus one standard deviation are presented for high tide and low tide observations.

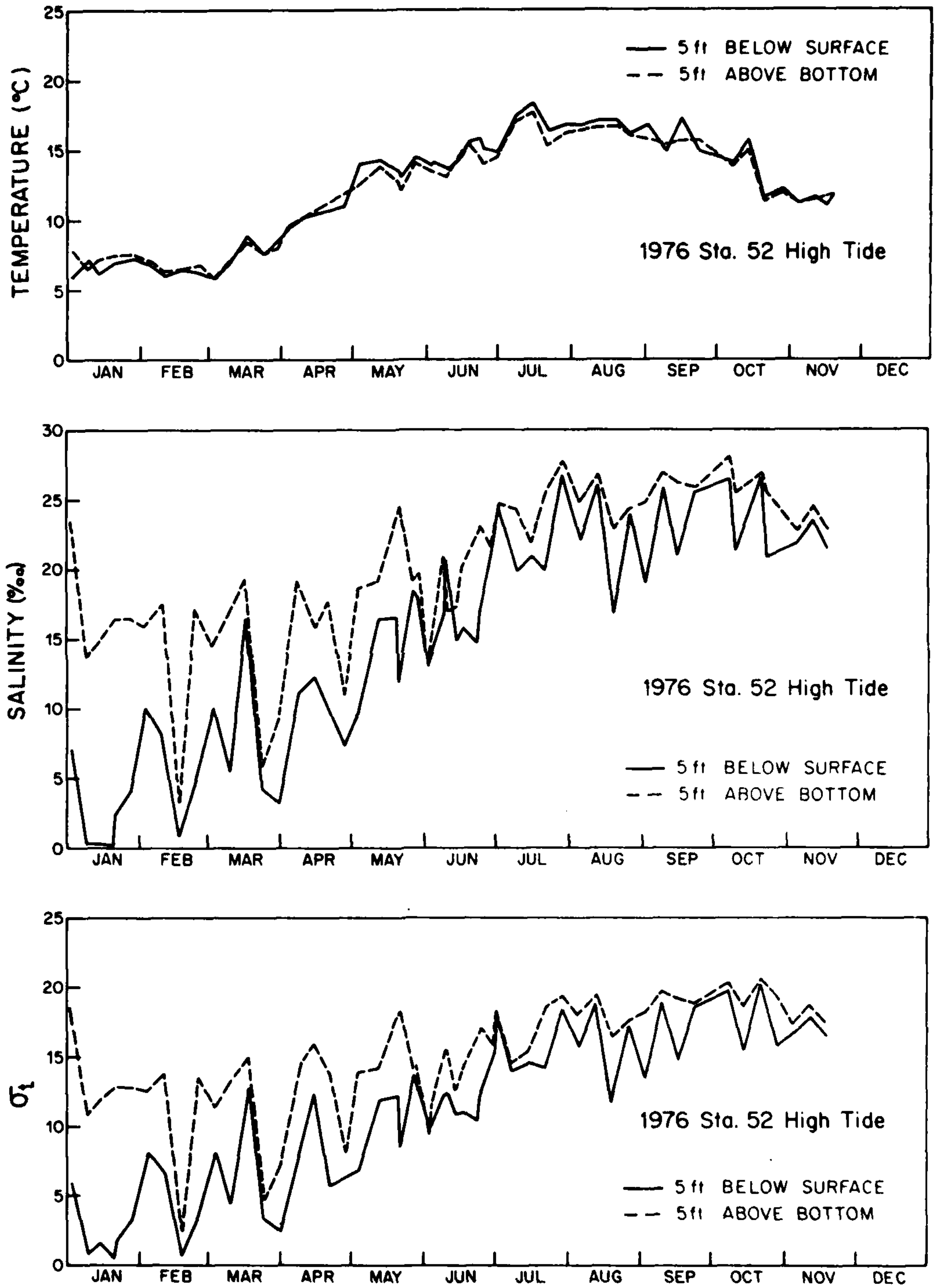


Figure 3-27. Temperature, salinity and density at high tide for Station 52 off Rennie Island during 1976

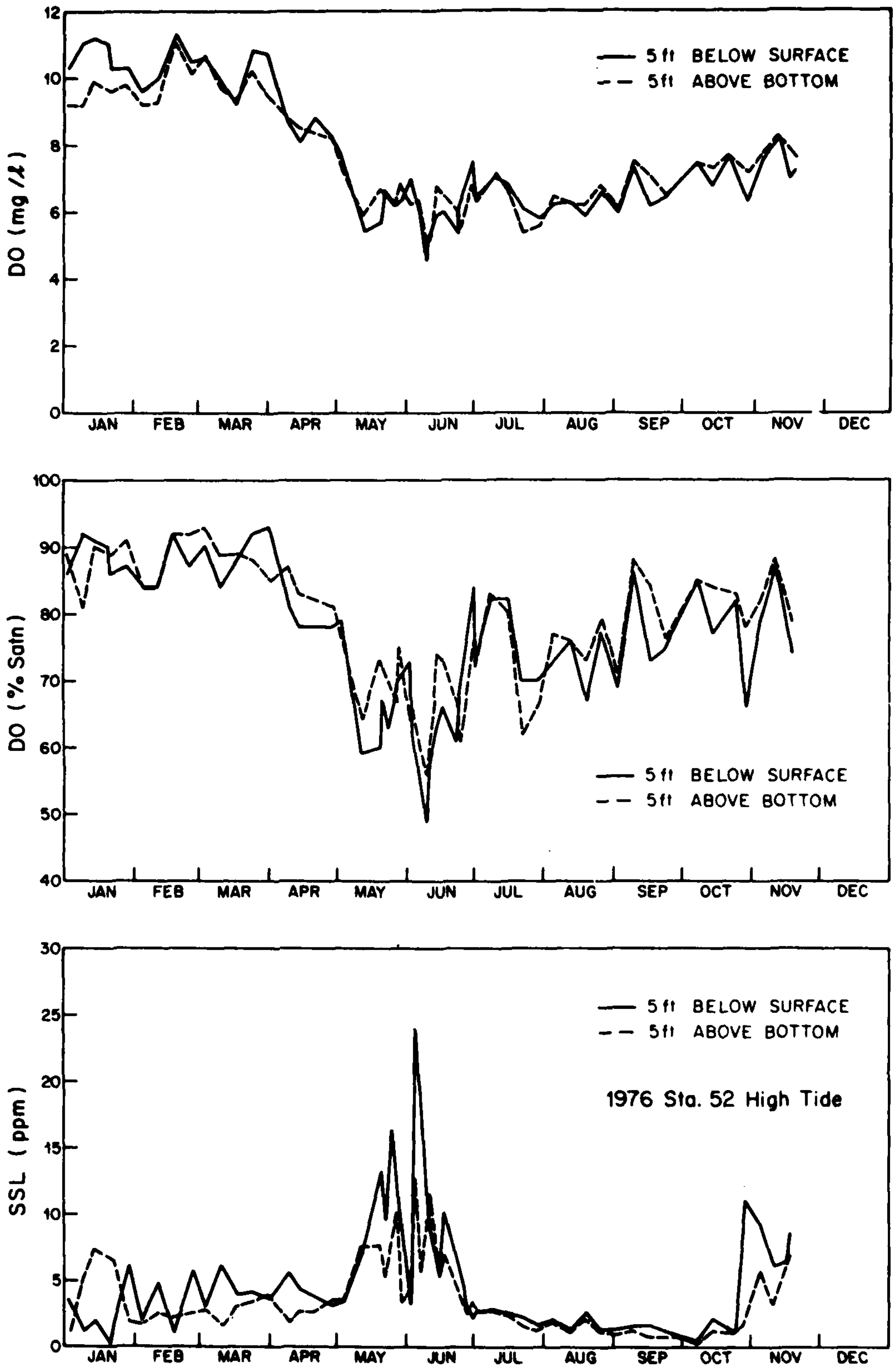


Figure 3-28. Dissolved oxygen, dissolved oxygen saturation and spent sulfite liquor for Station 52 off Rennie Island during 1976

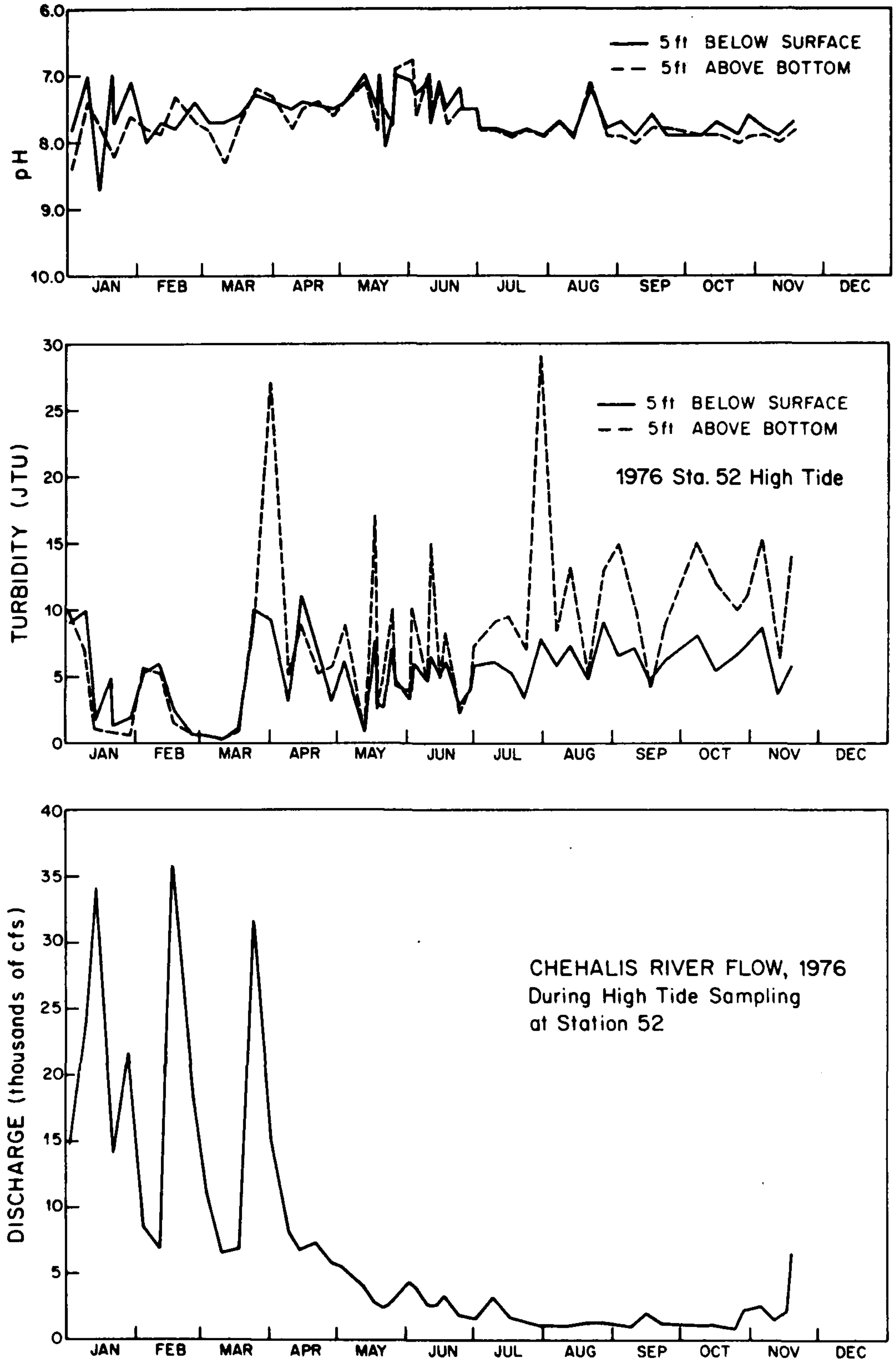


Figure 3-29. pH, turbidity and river discharge for Station 52 off Rennie Island during 1976

3.7 *Historical Changes in Factors Affecting Water Characteristics.*

The above data suggest that substantial changes in water characteristics have occurred in Grays Harbor resulting from industrial and municipal discharge practices that date back to the early 1920's. Table 3-2 lists key dates of industrial and municipal discharge practices affecting Grays Harbor. The trend in waste treatment in recent years has been to remove at the source those compounds influencing DO. Presently the pulp mills use their wastes either for sources of energy or for the extraction of chemical by-products.

Logging and agricultural practices have significantly affected the land cover in the Chehalis River watershed from the turn of the century to date. Removal of timber affects the amount and timing of river runoff and the temperature of the river water. Also, some of the rivers which are tributary to the Chehalis are regulated and discharge practices have been modified. Presently water is being released from the Wynoochee and Skookumchuck Reservoirs during periods of low flow so that the computed flow of the Chehalis at Aberdeen (section 3.1) rarely falls below 1,000 cfs. Summer flows less than 1,000 cfs were more common in years past.

The inputs of wastes with their high BOD and COD resulted in a decrease in DO in the inner harbor, most pronounced at times of low river flow. No measurements of DO are available from before 1938, so whatever the completely natural condition once was cannot be determined. From the 1938-39 data, it is apparent that at that time the DO was greatly depressed with values of less that 2.0 mg/l being measured during low flow conditions (Fig. 3-11). Changes in DO in the 1960's and 1970's for the summer low flow months are apparent for stations in the inner harbor (Figs. 3-25 and 3-26). Improvements in DO are directly related to improvements in discharge practices.

TABLE 3-2

DATES OF MAJOR CHANGES IN INDUSTRIAL AND MUNICIPAL
DISCHARGES INTO GRAYS HARBOR

1927 - Rayonier Plant began operation

1942 - Rayonier Plant began impoundment of mill wastes on Rennie Island during the summer months

1952 - Rennie Island impoundment capacity increased greatly

1957 - Weyerhaeuser Company began operation

1958 - Hoquiam went to secondary sewage treatment

1960 - Aberdeen and Cosmopolis started primary sewage treatment

1962 - Rayonier recovery system started, plus more diversion of summer wastes to Rennie Island. Recovery didn't function properly at this time.

1965 - Recovery system was completely operative at Rayonier Plant

1966 - Weyerhaeuser Company began secondary treatment of selected wastes during summer only (June to October)

1974 - Rayonier started primary treatment

1976 - Weyerhaeuser Company expanded secondary treatment of selected wastes to year round operation

1977 - Rayonier started secondary treatment system of all wastes and abandoned impoundment in summer at Rennie Island

Source: Roger Tollefson of ITT Rayonier, from telephone conversation of 8 July 1980.

4. GRAYS HARBOR CIRCULATION

4.1 *Factors Affecting Circulation*

The circulation in Grays Harbor is driven primarily by tidal action and secondarily by the density difference between the oceanic source water and the freshwater from rivers. Other factors influencing the circulation patterns include the the bathymetry of the basin, winds, changes in atmospheric pressure, coastal storm surges, entrainment of salt water in the fresher surface layer, and the Coriolis effect. The Coriolis effect is small in Grays Harbor and deflects the movement of he water to the right of the motion. All of these variables are continuously changing with time and have varying importance at any given period. Some of these factors will be discussed in more detail in the following sections.

4.2 *Effect of Bathymetry*

Circulation patterns are the result of tidally driven oscillating water movement interacting with the basin configuration and bathymetry. Localized eddies of varying dimensions develop as the water moves past bends in the channels, by points of land and over irregularities in bottom configuration. Eddies will be established on both ebb and flood current and will persist for the duration of that tide cycle. On reversal of the tide, the eddies will shift and die out with new eddies being formed in different locations.

The channel configuration is subject to both natural and man-made changes. Natural changes are slow and include the constant shifting of bottom sediments and the gradual filling of the estuary with fine sediments brought in by the rivers and from the coast (Milliman, 1963). Man-made changes are very rapid. A typical man-made change is the proposed widening and deepening project. The influence that any change in bathymetry will have upon the circulation patterns will depend upon the location and extent of change. Since the proposed widening and deepening project will be confined to existing channels, it is anticipated that any change in circulation will be confined to these channels.

4.3 *Tidal Effects*

Tides observed in Grays Harbor are of the Pacific Coast mixed type, meaning that two high tides and two low tides occur each tidal day (24.85 hrs). The two highs and two lows are of different heights with the greater

inequality occuring between the two lows. For Aberdeen the average daily range between low and high is 10.1 feet. In addition to daily changes in tide height, the time of the highs and lows shift each day and the tide range changes fortnightly and seasonally. The fortnightly change in range is evident in the shift from spring tide periods (greatest range) to neap tide (smallest range). Yearly changes occur so that the largest spring tide occurs in June during the daylight hours and in December the largest spring tide occurs at night. As a result of the continuously changing tide pattern, the tidally driven currents are continuously changing. Prediction of tidal currents in Grays Harbor have been made by the National Ocean Survey (NOS) for the entrance off Point Chehalis where the influence of the rivers is minimal.

Actual tide heights are the sum of the tides caused by astronomical forces, the effects of atmospheric pressure changes upon the water level, ocean wide changes in average sea level, river flow, and winds. All of these factors vary with time and most of these are not predictable. Only the tides caused by the astronomical forces are predictable. These predicted tides are published annually by the National Ocean Survey.

The effect of the tide extends upstream further than does the influx of salt water. Beverage and Swecker (1969) noted that tidal influences are observed many miles upstream from Montesano, the actual distance being a function of river flow and tide height. Since the river flow is superimposed upon the tidal currents, a net seaward current will occur at the surface. Hence, any particle of water originally brought in by the Chehalis River will eventually move to the ocean but in an oscillating fashion. Water leaving one segment of the estuary on the ebb will be mixed with water in the adjacent segment. On the following flood, this mixture becomes the source water for the original segment, a process known as "refluxing". As a result a parcle of water may move past the same geographic location several times before it finally leaves the area. This is especially true in the region where the "DO sag" is observed.

4.4 *Freshwater Effects*

The fresh water entering Grays Harbor has definite seasonal trends being greatest in winter and least in summer. Rivers respond rapidly to changes in precipitation in the watershed, peaking suddenly about three

days after the precipitation peaks at Hoquiam (Eriksen and Townsend, 1940). Discussions of circulation based upon monthly or seasonally averaged river flow often overlook the actual pulsating nature of the river discharge. Currents and corresponding flushing characteristics may be greatly influenced by this pulsation. A sudden large increase of river discharge may be followed by a marked change of DO and other water properties within the harbor.

The freshwater input has the effect of enhancing bottom and surface currents. As the fresher surface water moves seaward, salt water from below is entrained into the surface water. To replenish the entrained salt water, additional salt water must move along the bottom, thus producing a two-layered system. Additional freshwater flow will stimulate both a seaward surface transport of fresher water and a landward transport of seawater near the bottom. Also, this results in a density difference between top and bottom and from the seaward end to the landward end of the estuary. This density difference provides the secondary driving force for the curculation of Grays Harbor.

4.5 *Upwelling Effects*

Coastal upwelling occurs from June to September as a series if distinct events associated with winds having a strong northerly component. The effects of coastal upwelling on circulation may be significant within Grays Harbor because upwelled water is more dense than non-upwelled oceanic water. The density driven component of the circulation within Grays Harbor must adjust to changes occurring in the oceanic source water. If the density of the seawater and the river flow are held constant, a steady-state condition will develop. However, both the river flow and the density of the oceanic source water are constantly changing. Whatever the effects of upwelling on circulation may be, it must be recognized that a steady-state condition does not exist. After an upwelling event, the circulation in Grays Harbor will rapidly readjust to the "normal" condition. Duxbury (1979), in his study of flushing in Grays Harbor, concluded that the circulation of a coastal embayment bordering zones of active upwelling may be driven by the upwelling process during summer when river flow is reduced and upwelling is most intense.

4.6 *Field Measurements*

Very few direct observations of water currents have been made in Grays Harbor. Beverage and Swecker (1969) measured currents at selected stations and depths during four months of the year. Their observations periods were short, being from 13 to 25 hours in duration. Current measurements were made by the U.S. Army Corps of Engineers at several locations in Grays Harbor for use in verifying the physical model of Grays Harbor. These measurements were made from 4 to 17 October 1967. In all the number of direct observations of currents in Grays Harbor is very small and these are insufficient to accurately describe the circulation patterns in the harbor.

The direct observations showed a large variability of currents with different tide and river flow conditions. A comparison of surface and bottom currents by Beverage and Swecker showed that, the surface flow was usually strongest on the ebb tide (see Fig. 41). Dring periods of high river discharge, they observed that the surface and bottom flows were nearly identical at maximum ebb current and as the tide shifted to flood, the surface flow remained downstream throughout the flood. High river flow inhibited upstream tidal flow of the surface layer.

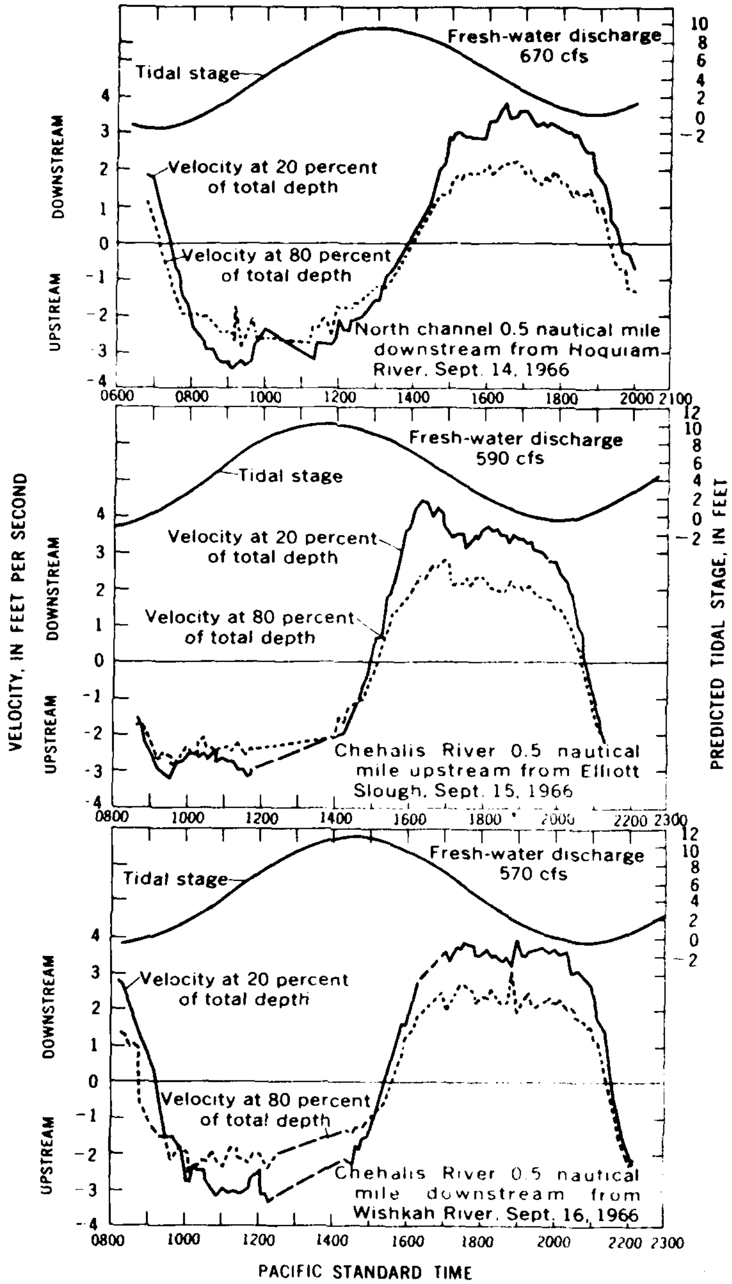


Figure 4-1. Point velocities at 20 and 80 percent of total depth at selected sites during the period 14-16 September 1966. Long dashes indicate missing data. (From Beverage and Swecker, 1969)

5. FLUSHING COMPUTATIONS

Numerous approaches have been utilized to evaluate flushing characteristics of Grays Harbor estuary. Flushing refers to the time required to completely replace the water in the estuary. Most methods were keyed to a particular condition of time, river flow and tide. Not all researchers evaluated flushing of the entire estuary, some preferring to evaluate only the inner harbor, and assumed that the outer harbor, with its tremendous intertidal volume, flushed rapidly.

Pearson and Gotaas (1951) computed flushing times for the entire estuary for the period 6 to 20 September 1950, when the average Chehalis River flow was approximately 800 cfs. Two different methods were employed. The first was based on the average concentration of spent sulfite liquor (SSL) present in the various parts of the harbor. The total volume of SSL present was computed and coupled with the known daily flow of SSL into the harbor, yielding a theoretical flushing time of approximately 21 days. The second method used was based on the average salinity in the harbor, from which the actual volume of fresh water present was computed. Assuming the average Chehalis River flow as the total fresh water inflow into the harbor, a theoretical flushing time of approximately 48 days was computed. The second method was considered to be the least accurate, due to the imprecision in measuring the total fresh water inflow to the harbor. Flow from the numerous other tributaries and from ground water seriously affect the accuracy of the flushing time computation based on salinity data.

Pearson and Gotaas computed theoretical flushing times for a segment of the inner harbor using both methods (SSL and salinity). Their inner harbor computation was bounded on the west by station 58 (one nautical mile east of the west end of Moon Island) and on the east by station 33 (just west of the Wishkaw River). The SSL method resulted in a 5.25 day flushing time and the salinity method gave an 11.2 day flushing time.

Pearson and Gotaas also computed detention times when the river flow was at 1300cfs following a shut down period for the pulp mill. The computed volume of SSL in the estuary was reduced approximately 50 percent in three days. Pearson and Gotaas stated that approximately 20 percent of the SSL was removed each day under this river flow and that the time required to flush 99 percent of the SSL in the harbor, assuming none was being added, was computed to be 21 days.

Callaway (1965) performed a flushing analysis using the modified tidal prism method of Ketchum (1951). For a river flow of 700 cfs, he determined that the flusing time for the entire lenght of the estuary was 5.5 days.

Stein and Denison (1965) noted that previous methods of computing flushing times for Grays Harbor required precise knowledge of freshwater flow (which is not availabe) and assumption of simple basin configurations (which does not apply to Grays Harbor). Stein and Denison devised an empirical method of computing flushing based on removal of SSL during a period of mill shutdown. For a river flow average of 2,730 cfs they found that about 19.1 percent of the waste was removed per day. The field methods employed involved concentrated sampling within Hoquiam Reach, whereas the methods employed by Pearson and Gotaas involved less frequent sampling that covered much more of the estuary. The 19.1 percent removal per day within the Hoquiam Reach study area compares very favorably with the 20 percent removal per day computed by Pearson and Gotaas for the same area, although the river flow for Pearson and Gotaas was less.

Duxbury (1979) used a salt and freshwater budget approach to estimate flushing rates for the inner harbor. Given the 1965-69 data base from ITT Rayonier, Duxbury computed monthly average rates of outflowing water and by comparison with the volume of the inner harbor, derived the percent replacement per day and the residence time in days for the monthly averages. These values are presented in Table 5-1.

TABLE 5-1

REPLACEMENT RATES AND RESIDENCE TIMES
OF INNER HARBOR WATER

Month	Total Seaward Flow* ($\times 10^6 m^3$/day)	% Replacement per day	Residence time (days)
JAN	102.6	166	0.60
FEB	81.4	132	0.76
MAR	65.4	106	0.94
APR	39.4	64	1.56
MAY	22.6	36	2.78
JUN	20.5	33	3.03
JUL	12.5	20	5.00
AUG	18.2	29	3.45
SEP	33.7	55	1.82
OCT	50.0	81	1.24
NOV	43.8	71	1.41
DEC	83.8	135	0.74

After: Duxbury (1979)

*equals total freshwater in plus salt water in.

6. MONITORING REQUIREMENTS DURING DREDGING

The U.S. Army Corps of Engineers is currently required by the Washington State Department of Ecology (WDE) to monitor dissolved oxygen (DO), turbidity, temperature, and salinity during dredging operations when the Chehalis River flow at Aberdeen drops below 2,500 cfs. According to a spokesperson for WDE, this river flow criteria was arbitrarily set more than 14 years ago, by mutual agreement between many regulatory agencies, when the influence of the pulp mills was substantially greater than it is now. Low DO in the inner harbor was of primary concern at that time.

Since the monitoring requirements were established, waste treatment practices by industry and municipalities have reduced the biological oxygen demand of their effluent. As a result, the minimum DO in Grays Harbor has increased to a point where present day values seldom fall below the water quality standard of 5.0 ppm set for Grays Harbor.

In our analysis of the extensive data base prepared for this study, we evaluated the water characteristics data for several river flow increments. Water characteristics for the increment of 1,500 to 2,000 cfs were very similar to those in the increments of 2,000 to 2,500 cfs and 2,500 to 3,000 cfs. For river flows less than 1,500 cfs, the conservative properties (temperature and salinity) showed significant increases throughout the inner harbor. Dissolved oxygen, a non-conservative property, showed very little difference for the increments of 1,500-2,000, 2,000-2,500, and 2,500-3,000 cfs while showing a significant decrease below 1,500 cfs. Mean monthly DO values at high tide for the east end of Aberdeen Reach were computed the two year periods of 1974-75, 1976-77 and 1978-79. The mean DO values fell below 6 ppm six times and five of these were for mean river flows of less than 1,500 cfs. No significant difference in water characteristics can be distinguished for the flow increment which brackets the present 2,500 cfs monitoring criteria. Therefore, we suggest that monitoring be continued but only for river flows below 1,500 cfs at Aberdeen.

7. EVALUATION OF DISSOLVED OXYGEN MATHEMATICAL MODELS

7.1 *Introduction*

Three mathematical models have been developed for the prediction of dissolved oxygen (DO) concentrations in the waters of Grays Harbor; one by Battelle Northwest, one by Water Resources Engineers (WRE), and a third by Region X of the Environmental Protection Agency (EPA). These models used similar computational methods, were all written in FORTRAN, and represent successive generations in mathematical modeling. Attempts were made to obtain documentation and source decks (IBM cards of the programs) for each of the models. Instruction manuals and a listing of the Battelle model (Battelle, 1974) were obtained but no source deck was available. The WRE model was specifically designed for Puget Sound and not for Grays Harbor. The EPA model was a refinement of the Battelle model and incorporated many of the computational techniques used by the WRE model. The authors were able to obtain documentation (Cleland, 1978) and a source deck for the EPA model.

After a careful review of the available documentation for each model, the authors decided to implement the EPA model. This model was selected because it was specifically written ("tuned") for Grays Harbor, incorporated the best features of both the Battell and WRE models, and because the authors were able to communicate directly with Mr. Bruce Cleland, the person who actualy developed this model. (Mr. Bruce Cleland is currently employed by Region X of EPA.) Cleland subdivided Grays Harbor into much smaller segments than did the programmers of the Battellė model and also accounted for changes in slope of the shoreline from mean lower low water (MLLW) to mean higher high water (MHHW). Cleland supplied the authors with a copy of the source deck of the model and a data deck. Cleland had adapted the model for use on a PDP-11 computer. The authors then modified this program to run on a PRIME 300 computer.

7.2 *Description of the EPA Model*

The mathematical model developed by EPA is a link-node type meaning that the area being studied is subdivided into many small segments. Grays Harbor was divided into 79 boxes (called junctions) that were connected to each other by 100 "hoses" (called channels). Figure 7-1 shows the location of the junctions. The mathematics of this model also created a dynamic model in which the water level is made to change with time corresponding to

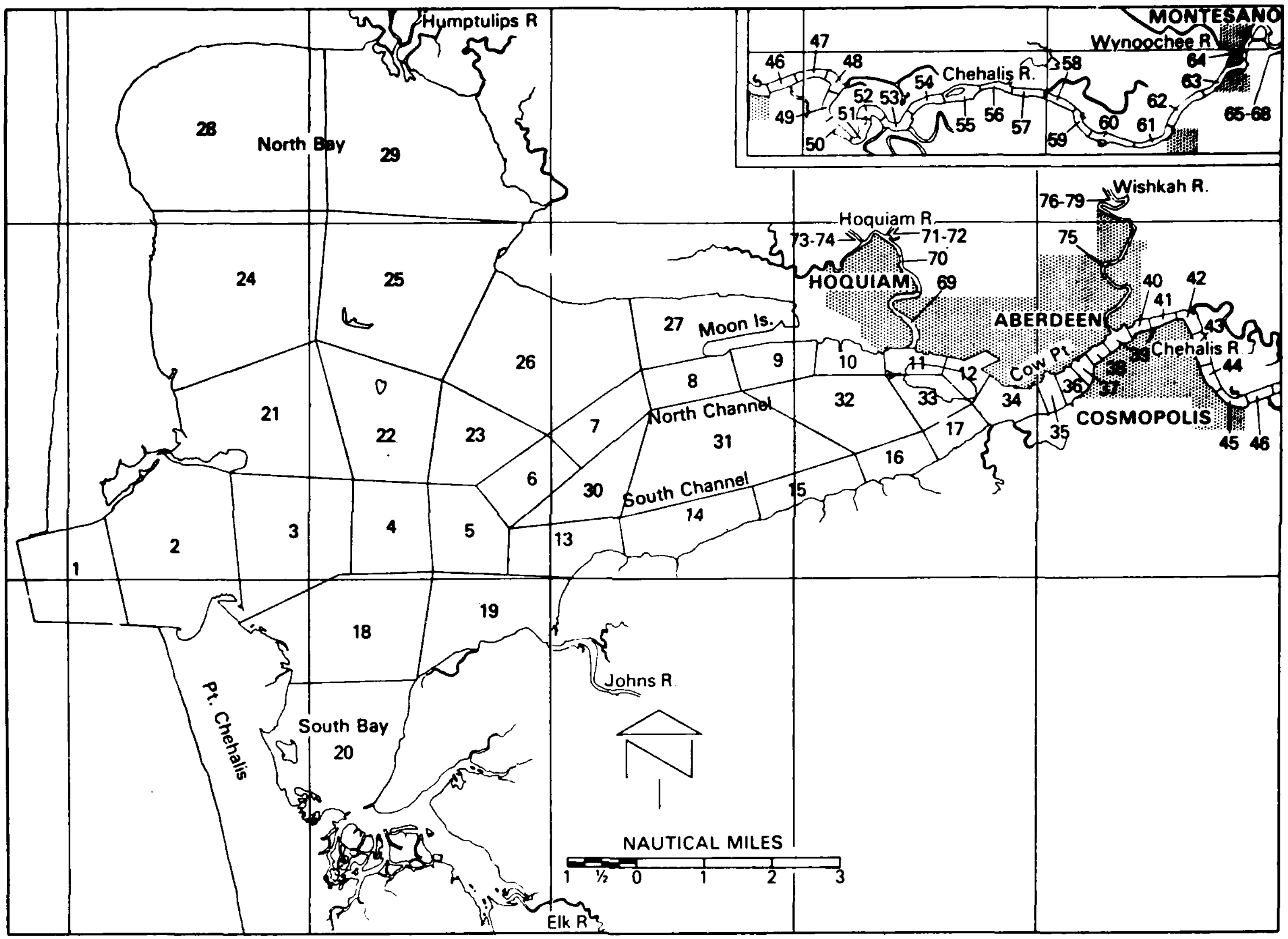


Figure 7-1. Divisions and junctions of the mathematical model of Grays Harbor developed by the EPA. (From Cleland, 1978)

the tide. Water is forced to move back and forth within the junctions of the Grays Harbor model through the channels, and changes in DO are predicted in response to this flow and other time dependent variables. Inputs to the model included the geometry of the junctions and channels, the predicted tide curve at Westport, river and other freshwater inputs, and the initial conditions of temperature, salinity, DO, and nutrients in each of the 79 junctions. Each of the major variables will be discussed in detail in section 7.3.

The DO concentration was determined for each junction along the channel axis for each 15-minute interval throughout a given day by the equation:

(DO at time 1) = (DO at time 0) + (total DO entering the junction in this time interval) - (DO leaving the junction in the same time interval) (7.1)

or simply for a given junction

$$DO_{new} = DO_{old} + DO_{in} - DO_{out} \qquad (7.2)$$

For each junction, DO_{old} is given either by the initial conditions at time 0 or by the conditions existing at the end of the time interval just computed. DO_{in} is computed for each source and sink of oxygen for a given junction and includes oxygen generated by photosynthetic processes, diffusion of oxygen across the air-water interface, oxygen being advected into the specified junction from adjacent junctions, and from any other freshwater source entering the junction. Similarly, DO_{out} included any DO flowing out of the junction into adjacent junctions, any DO utilized by zooplankton, any biological oxygen demand (BOD) and chemical oxygen demand (COD), and any oxygen used by the bottom sediments. Many of these factors are poorly understood so the equations used to compute the effects of these factors on DO are at best only estimates and should be critically reviewed. These factors have spatial and seasonal variablity that are not completely accounted for by the equations written to account for the DO.

One drawback of the link-node type model is that the system being modeled is treated as a *one-dimensional* system so any vertical or horizontal variability in a given junction is not considered. This *one-dimensional* approach was necessary to keep the model to a reasonable size and the computer time required for a single run to acceptable amounts. The results obtained from such an integrated model that ignores stratification and the

typical two-layered flow of an estuary must be critically examined for credibility.

The mathematical model is a very large computer program requiring a large amount of computer memory. Cleland (1978) divided the model into three main-line programs so it could be run on a computer with only a 64K memory. The first program (ECOHYD) computed the hydrodynamic conditions of tidal volume changes within each junction and the required flow through the connecting channels. The second program (ECOWEA) was used to compute selected meteorological parameters. The third program (ECOSIM) computed the amount of DO and other parameters. The nature of the inputs to the programs and calendar dates to be evaluated can be selected as can the parameters to be computed (DO, temperature, salinity, and others). The junctions for which these parameters are to be reported can also be specified. It is the specifying of data from only those junctions along the longitudinal axis of the estuary that makes the model *one-dimensional.*

7.3 *Inputs to the Programs*

The program ECOHYD uses the geometry of Grays Harbor and the freshwater inputs to compute the exchange of water between the various junctions by solving the equation of long-wave propagation through a shallow water system and by satisfying the equations of continuity. It is the inputs to this program that must be altered to compute any effect of the proposed widening and deepening of the Grays Harbor navigation channel may have upon the distribution of DO. Inputs to ECOHYD are as follows:

At the entrance--

The predicted tide heights and times for a specified date.

For each channel--

1. The elevation of local MLLW below the National Geodetic Vertical Datum as referred to Point Chehalis,
2. The length of the channel,
3. The width of the channel averaged over its length,
4. The hydraulic radius based upon the average depth of the channel over its length,
5. The "Manning" coefficient, a measure of the frictional resistance of the water passing over the sea floor, and
6. The numeric designators of the two junctions connected to each other by this channel.

For each junction--

1. The surface area of the junction at MLLW,
2. The average depth of water in the junction below MLLW,
3. The change in surface area with change in tide height from MLLW to MHHW,
4. The inputs of freshwater from any river or municipal source adjacent to the junction, and
5. The numeric designation of all channels flowing into this junction.

To obtain the necessary geometric data for ECOHYD, the areas confined within selected depth contours were determined from the National Ocean Survey (NOS) chart No. 18052 of Grays Harbor, dated 15 October 1977. Then the volume of water contained within each junction and within each channel was computed, the average depth below MLLW for each junction determined, and the hydraulic radius for each channel estimated. For exact details of the method used see Cleland (1978).

In order to evaluate the effect of the proposed widening and deepening project upon DO it is necessary to determine the change of depth of the affected junctions and channels. This was done by first computing the volume of the original navigational channel as given on the NOS chart 18052 for the affected junctions, namely junctions 6 through 12 and 34 through 44. Then the volume of the proposed channel as specified in the Feasibility Study (US Army Corps of Engineers, 1977) was computed. The difference between the pre-dredge and post-dredge volumes for each junction was added to the original volume of the junction at MLLW. Since the surface area of the model junctions at MLLW is not affected by dredging, a new average depth for each affected junction is required. Finally, the hydraulic radius of the affected channels was estimated. These new values were then used to modify the original input data. The changes in depth incorporated into the new data deck are listed in Table 7-1.

For the program ECOWEA, meteorological data at three-hour intervals for the dates to be run by ECOSIM and ECOHYD are supplied. These data include the dry and wet bulb air temperature, wind speed, cloud cover, and evaporation rate.

Data used by the simulation program (ECOSIM) were much more complex than those used by the other programs. ECOSIM must account for biological processes that in turn affect the DO distribution throughout Grays

TABLE 7-1

CHANGES IN DEPTHS OF JUNCTIONS AND CHANNELS AS AFFECTED BY THE PROPOSED WIDENING AND DEEPENING OF THE NAVIGATIONAL CHANNEL IN GRAYS HARBOR

JUNCTION			CHANNEL		
	Depths (in feet)			Depths (in feet)	
Number	Before	After	Number	Before	After
6	26.2	27.2	6	16.1	17.3
7	24.5	25.5	7	15.2	16.8
8	24.9	26.9	8	12.7	14.6
9	19.6	21.6	9	12.2	14.4
10	23.8	27.5	10	14.8	18.0
11	24.8	28.5	11	15.6	20.7
12	25.4	29.1	12	24.2	26.9
34	23.7	26.7	56	13.5	14.7
35	22.4	23.5	57	13.1	15.6
36	22.8	24.3	58	13.4	15.9
37	23.2	26.0	59	13.8	16.3
38	23.5	26.3	60	14.1	16.6
39	23.7	29.5	61	14.4	16.9
40	24.0	28.8	62	14.6	17.1
41	24.3	29.1	63	14.9	17.9
42	24.6	30.0	64	15.2	17.7
43	24.9	24.3	65	17.7	21.7
44	25.3	33.9			

Harbor. In addition to data supplied as input, ECOSIM also used the output of ECOHYD for water movement and the output of ECOWEA for the meteorological conditions.

Many of the factors affecting DO are spatially, time, and temperature dependent. Decay and temperature coefficients were specified for BOD, detritus, spent sulphite liquor (SSL), coliform bacteria, ammonia, and nitrite. The "average" chemical compositions for algae, zooplankton, fish, benthos, and detritus were also included as input to ECOSIM. Oxygen demand rates for bottom sediments were specified for each junction. These rates were obtained from a study by EPA in which the oxygen demand rates of the sediments were determined for three sites in Grays Harbor on one day (Kreizenbeck, 1973). Water characteristics for each junction were specified for the beginning of the desired time period. These included temperature, salinity, DO, BOD, and nutrients. The freshwater flow and chemical composition for industrial and municipal discharges were given for each junction where fresh water entered. These parameters were specified in the data file used by ECOSIM. Any of these values may be modifed as desired. But if any variable supplied to ECOSIM, ECOWEA, or ECOHYD is varied, any or all of these programs must be rerun before the final desired results are obtained.

7.4 *Outputs of the Programs*

The hydrodynamic computation program (ECOHYD) computed predicted changes in tide height, volume of water in the junctions, and the flow rates in each channel at 45-second intervals. This interval was determined by Cleland (1978) to be the optimum interval in order to prevent instability of the computations that may be introduced by the mathematical processes used in the programs. These computed values were then averaged over 15-minute intervals and transferred to magnetic tape for later use by ECOSOM. At the end of each days computations, a summary of the water-level at selected junctions and the flows in selected channels were printed and plotted. Figure 7-2 shows a typical plot of water-level for 25 July 1977. In addition the input data and selected intermediate results are printed.

The weather prediction program (ECOWEA) computed changes in solar radiation, evaporation, and wind speeds at hourly intervals and stored the results on disk for later use by ECOSIM. Also, the results were printed for each data point computed.

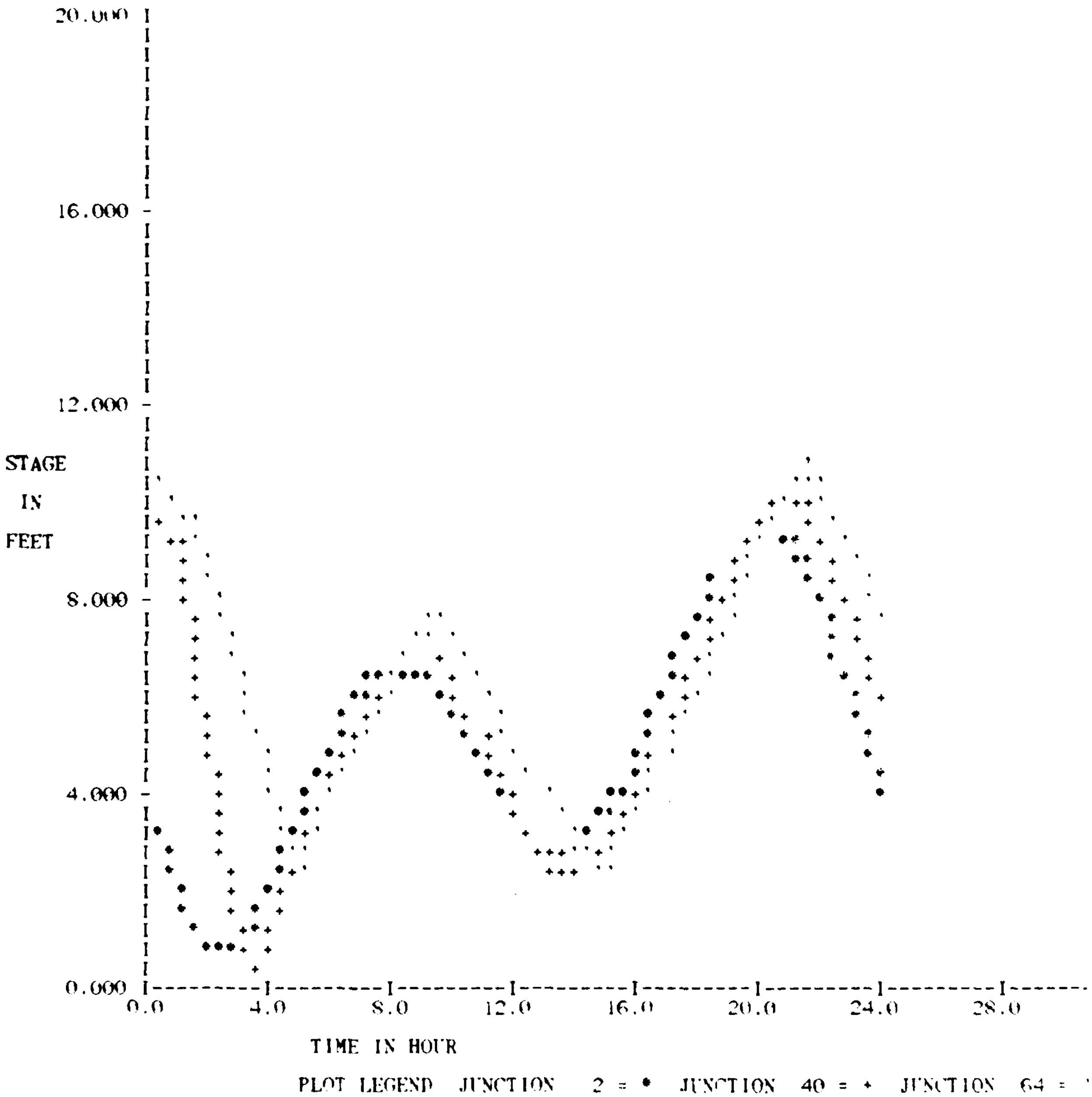


Figure 7-2. Plot of water level for selected junctions for 25 July 1977 as generated by the EPA mathematical model.

The water characteristics simulation program (ECOSIM) computed changes in selected water properties at 15-minute intervals and then averaged these values over hourly intervals for each day being simulated. These data were stored on disk for future use and were printed in tabular form. A typical output from ECOSIM is presented in Figure 7-3.

7.5 *Evaluation of Results from the Mathematical Model*

The purpose of any model, whether physical or mathematical, is to predict contitions in the prototype when selected variables are modified. To do this, a model is adjusted to accurately reproduce the conditions in the prototype for a given date or series of dates. Then by modifying the input to the model (such as widening and deepening a navigation channel), the effects of these modifications on selected parameters may be studied. To be acceptable, the model must predict the changes in the natural system with a high level of confidence. In the case of Grays Harbor, the model must reproduce the water-level at various times and locations throughout the harbor. But more important, it must reproduce the distribution of the desired water property, in this case DO, both in space and time. The discussion in Section 3 stipulated that the important aspects of the DO distribution are the presence and migration of the "DO sag" (see Figs. 3-9 and 3-10) and the tidal periodicity in DO concentration at fixed locations (see Figs. 3-11 and 3-12).

In order to make the mathematical model agree with nature for a test case, it was necessary to adjust the various coefficients of the equations used to compute water-level, flow in the channels, and the factors affecting the distribution of water properties. The coefficients used in ECOHYD were adjusted by Cleland until the water-levels computed by ECOHYD agreed with those actually measured throughout Grays Harbor for the test period of 25 to 30 July 1977. A survey of water properties in Grays Harbor from the entrance to Cosmopolis was made by EPA for the same time period. From these data, Cleland adjusted the coefficients of the equations in ECOSIM that controlled the DO concentration until he obtained an approximate simulation of the observed DO distribution. His adjusted results appeared to be in good agreement with the data actually obtained in the field if one considers the DO distribution to be fixed in space along the major axis of the navigation channel in Grays Harbor.

The first column is the parameter reported: 1 = temperature, 3 = salinity, 5 = BOD, 6 = DO

The numbers following are the junctions for which the parameters are reported.

```
WRITING CONTENTS OF EXOSIM.HST
N   1        2    3    4    5    6    9   11   13   14   15   16
N   1       21   24   34   40   46   49   52   55   61    0    0
N   3        2    3    4    5    6    9   11   13   14   15   16
N   3       21   24   34   40   46   49   52   55   61    0    0
N   5        2    4    6    9   11   34   40   46   49   55   61
N   6        2    3    4    5    6    9   11   13   14   15   16
N   6       21   24   34   40   46   49   52   55   61    0    0

 1  206  1.0   10.20   9.94  10.40  10.30  10.20  10.70  12.40  11.00  11.00  10.30  10.50
 1  206  1.0    8.75   8.18  13.20  14.30  14.80  14.70  14.30  14.10  13.70   0.00   0.00
 3  206  1.0   31.00  31.00  30.00  30.00  28.50  26.50  23.50  28.50  26.50  26.50  23.50
 3  206  1.0   30.00  30.00  22.50  17.00  11.50   8.00   5.00   2.50   0.50   0.00   0.00
 5  206  1.0    1.19   1.48   1.91   2.19   2.03   2.03   1.59   1.30   1.15   1.58   1.73
 6  206  1.0    7.07   7.08   6.96   6.95   6.53   5.66   5.08   6.43   6.34   6.05   5.13
 6  206  1.0    6.84   6.93   5.02   5.53   6.19   6.78   7.30   7.80   8.32   0.00   0.00

 1  206  2.0    9.77   9.50  10.20  10.20  10.00  11.20  12.60  10.70  10.60  10.40  11.20
 1  206  2.0    8.19   7.14  13.30  14.50  14.60  14.30  14.00  13.90  13.50   0.00   0.00
 3  206  2.0   31.00  31.00  30.00  30.00  28.50  26.50  23.50  28.50  26.50  26.50  23.50
 3  206  2.0   30.00  30.00  22.50  17.00  11.50   8.00   5.00   2.50   0.50   0.00   0.00
 5  206  2.0    1.18   1.47   1.90   2.18   2.02   2.01   1.58   1.29   1.15   1.57   1.72
 6  206  2.0    7.10   7.11   6.99   6.98   6.58   5.70   5.10   6.45   6.37   6.07   5.18
 6  206  2.0    6.89   7.00   5.01   5.54   6.19   6.78   7.30   7.80   8.32   0.00   0.00

 1  206  3.0    9.62   9.31  10.20  10.30  10.30  12.10  13.10  10.70  10.80  11.30  12.80
 1  206  3.0    7.90   6.77  13.80  14.70  14.40  14.10  13.90  13.70  13.30   0.00   0.00
 3  206  3.0   31.00  31.00  30.00  30.00  28.50  26.50  23.50  28.50  26.50  26.50  23.50
 3  206  3.0   30.00  30.00  22.50  17.00  11.50   8.00   5.00   2.50   0.50   0.00   0.00
 5  206  3.0    1.18   1.47   1.90   2.17   2.01   2.00   1.57   1.28   1.14   1.57   1.71
 6  206  3.0    7.12   7.13   7.00   6.99   6.61   5.73   5.12   6.47   6.37   6.07   5.20
 6  206  3.0    6.94   7.08   5.01   5.54   6.20   6.80   7.32   7.82   8.34   0.00   0.00

 1  206  4.0   10.30   9.40  10.10  10.40  10.30  12.50  13.60  10.70  10.90  11.60  13.00
 1  206  4.0    7.97   6.90  14.20  14.90  14.60  14.20  14.00  13.70  13.10   0.00   0.00
 3  206  4.0   31.00  31.00  30.00  30.00  28.50  26.50  23.50  28.50  26.50  26.50  23.50
 3  206  4.0   30.00  30.00  22.50  17.00  11.50   8.00   5.00   2.50   0.50   0.00   0.00
 5  206  4.0    1.17   1.46   1.89   2.15   2.00   1.99   1.56   1.27   1.13   1.56   1.70
 6  206  4.0    7.12   7.13   7.00   6.99   6.65   5.72   5.11   6.52   6.36   6.05   5.18
 6  206  4.0    6.95   7.13   4.98   5.52   6.20   6.81   7.34   7.84   8.36   0.00   0.00

 1  206  5.0   11.60  10.20   9.98  10.20  10.30  11.80  13.10  10.60  10.80  11.30  12.20
 1  206  5.0    8.43   7.05  13.90  14.80  14.60  14.20  14.20  13.90  13.40   0.00   0.00
 3  206  5.0   31.00  31.00  30.00  30.00  28.50  26.50  23.50  28.50  26.50  26.50  23.50
 3  206  5.0   30.00  30.00  22.50  17.00  11.50   8.00   5.00   2.50   0.56   0.00   0.00
 5  206  5.0    1.17   1.45   1.88   2.14   1.99   1.98   1.55   1.27   1.13   1.55   1.69
 6  206  5.0    7.12   7.14   7.00   7.00   6.65   5.72   5.10   6.52   6.37   6.04   5.18
 6  206  5.0    6.96   7.16   4.96   5.50   6.19   6.81   7.34   7.85   8.39   0.00   0.00
```

First column is the parameter code. Second column is the day number (206 = 25 July 1977). Third column is the time of day. Remaining columns are the values of the parameter at the junctions indicated in the header.

Figure 7-3 Typical output of selected water characteristics as predicted by the EPA mathematical model

To test how the model would predict changes brought about by the proposed dredging, of the navigation channel in Grays Harbor, two sets of data for the channel configuration were used. The first set of data was the original bottom configuration data as supplied by EPA and provided the hydrological data *before* the channel was dredged. The second data set was for the channel configuration *after* dredging as described in section 7-3. Both sets of data were run using ECOHYD for the test date of 25 July 1977. The actual flow of the Cehalis River at Aberdeen for this date was 1,200 cfs. Next ECOSIM was run twice holding all parameters constant except for the output of ECOHYD. Thus a comparison of the two sets of output from ECOSIM would provide a measure of the predicted changes brought on by the dredging project.

In evaluating the results from ECOSIM, it must be remembered that the mathematical model treats Grays Harbor as a *one-dimensional* system and that the results are *averages* of the DO concentration over all of the water volume contained within each junction. A comparison of the DO concentration for the *before* and *after* dredging conditions as predicted by ECOSIM are given in Table 7-2 for junctions 34, 40, and 46 (see Fig. 7-1 for location). From this table, it is evident that no tidal periodicity in DO concentration was predicted. However, these results did indicate that a slight increase in DO of 0.01 to 0.05 ppm may occur after dredging.

In order to determine if the mathematical model would show the migration of the "DO sag", a comparison of *actual* and *predicted* DO distributions along the channel from the Entrance Reach to Cosmopolis was made. Figure 7-4 shows that no migration of the "DO sag" was predicted. The DO minimum remained in the same position for both low and high tide. A comparison of the *before* and *after* cases with the *actual* data was not necessary because the results from these cases were nearly identical. Observations in the field show that the "DO sag" migrates and this is an important feature of the water characteristics of Grays Harbor. Failure of the model to predict this tidal excursion of the DO sag, which may be 8 or more miles, is a definite weakness and makes it nearly useless as a predictive tool.

From the results of these two comparisons, it is our conclusion that the EPA model, even though it is the best mathematical model available today for Grays Harbor, does not accurately reproduce the dynamics of the system as it showed neither a tidal periodicity of DO near Cow Point (junction 34) nor

TABLE 7-2

Comparison of dissolved oxygen
for three junctions as predicted by the
EPA model for before and after dredging

DATE: 25 July 1977

TIME	JUNCTION 34 Cow Point Before	After	Change	JUNCTION 40 Near Wishkah River Before	After	Change	JUNCTION 46 East of Cosmopolis Before	After	Change
0100	5.02	5.05	+0.03	5.53	5.54	+0.01	6.19	6.20	+0.01
0200	5.01	5.05	+0.04	5.54	5.55	+0.01	6.19	6.20	+0.01
0300	5.01	50.4	+0.03	5.54	5.54	--	6.20	6.21	+0.01
0400	4.98	5.02	+0.04	5.52	5.52	--	6.20	6.20	--
0500	4.98	5.00	+0.02	5.50	5.51	+0.01	6.19	6.19	--
0600	4.94	4.98	+0.04	5.49	5.49	--	6.18	6.18	--
0700	4.92	4.95	+0.03	5.47	5.48	+0.01	6.17	6.17	--
0800	4.90	4.93	+0.03	5.46	5.46	--	6.16	6.17	+0.01
0900	4.87	4.91	+0.04	5.45	5.45	--	6.15	6.16	+0.01
1000	4.85	4.89	+0.04	5.43	5.43	--	6.14	6.15	+0.01
1100	4.83	4.88	+0.05	5.42	5.42	--	6.13	6.14	+0.01
1200	4.81	4.86	+0.05	5.41	5.41	--	6.13	6.13	--
1300	4.79	4.83	+0.04	5.39	5.39	--	6.12	6.13	+0.01
1400	4.76	4.81	+0.05	5.37	5.37	--	6.11	6.11	--
1500	4.73	4.78	+0.05	5.34	5.35	+0.01	6.09	6.10	+0.01
1600	4.71	4.76	+0.05	5.33	5.33	--	6.08	6.09	+0.01
1700	4.69	4.74	+0.05	5.31	5.32	+0.01	6.07	6.08	+0.01
1800	4.68	4.73	+0.05	5.31	5.31	--	6.07	6.08	+0.01
1900	4.66	4.71	+0.05	5.30	5.31	+0.01	6.07	6.06	-0.01
2000	4.65	4.70	+0.05	5.30	5.30	--	6.06	6.07	+0.01
2100	4.63	4.68	+0.05	5.29	5.29	--	6.05	6.06	+0.01
2200	4.61	4.66	+0.05	5.28	5.28	--	6.04	6.05	+0.01
2300	4.60	4.65	+0.05	5.28	5.27	-0.01	6.04	6.05	+0.01
2400	4.58	4.64	+0.06	5.28	5.27	-0.01	6.04	6.05	+0.01

Note: dissolved oxygen units are miligrams per liter (mg/l).

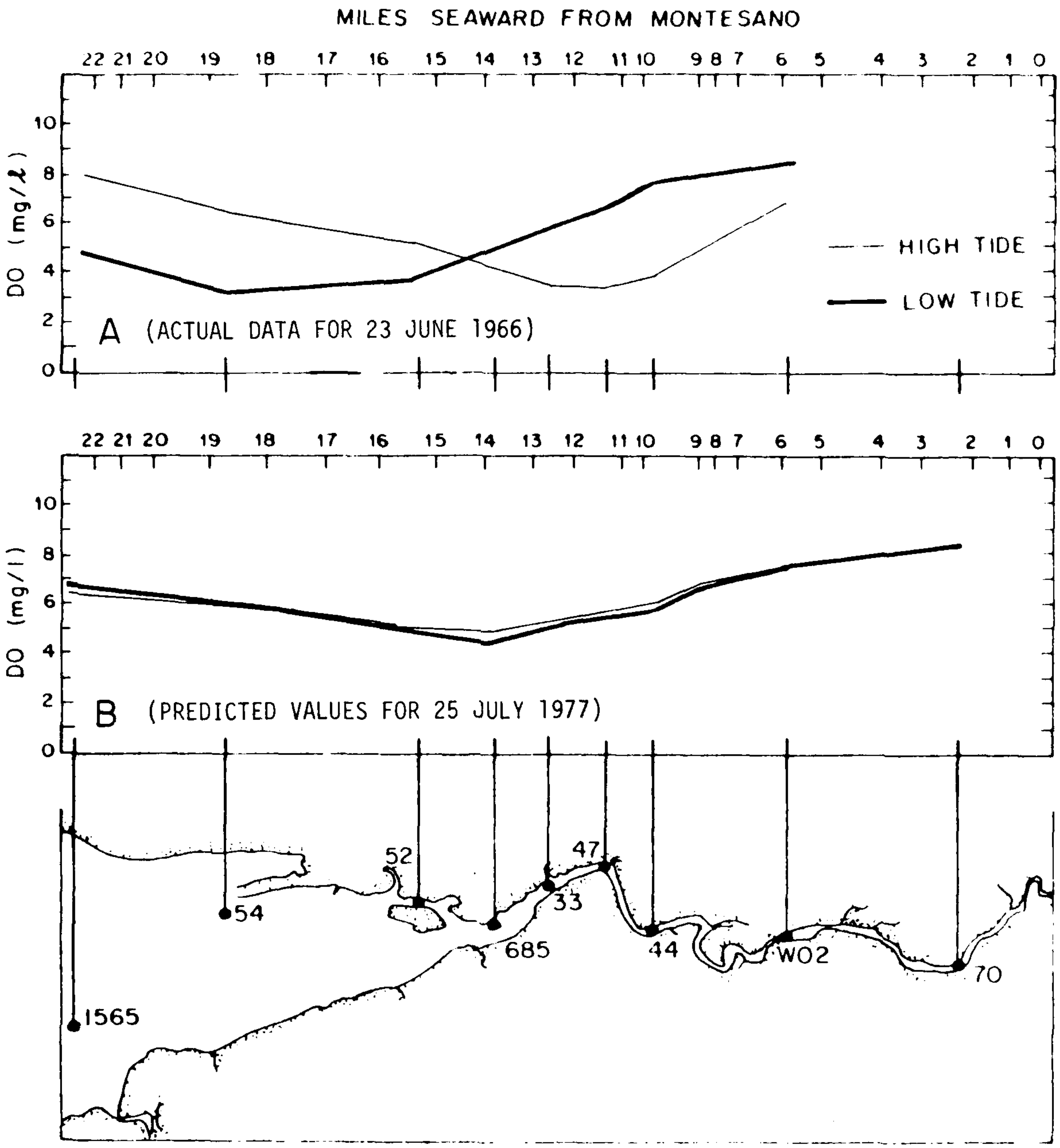


Figure 7-4. Comparison of actual and predicted concentrations of dissolved oxygen for nearly identical tide ranges. (Note - the mathematical model predicted values did not show the migration of the "DO sag".)

a tidal migration of the "DO sag" along the channel. Cleland did not have the extensive data base with which to work and tune the model that is available for this report. Hence, when he "verified" the model, he was not aware of the tidal migration of the "DO sag."

7.6 *Continued use of the Mathematical Model*

At present we conclude it is not feasible to use the existing EPA mathematical model as a predictive tool to study water parameter changes caused by widening and deepening in Grays Harbor as the model does not accurately reproduce the actual spatial and temporal distributions of DO in Grays Harbor. One reason is that some of the factors that affect DO such as BOD and COD migrate with the water once any effluent is introduced into the water and are not confined to the model junction in which they were introduced. The model treats all factors affecting DO as being stationary in space. Another reason is that the EPA model treats Grays Harbor as a *one-dimensional* entity in which any variation of water characteristics or flow in either the horizontal or vertical is averaged over the entire water volume contained within the given junction. The actual field observations (Figs. 3-27 to 3-29) indicate that the water column is usually stratified and that a two-layered flow exists.

In order to introduce stratification into the mathematical model, it will be necessary to divide each junction into an upper and a lower sub-junction with appropriate connecting channels between each layer. To account for the migration of BOD and COD and other factors affecting DO, the equations must be modified and the model reprogrammed. One aid in reducing the size of the model in terms of data stored and manipulated would be to restrict the geographic area covered by making the seaward end of the model begin at the west end of junction 6 and subdividing into smaller junctions. In all, a substantial amount of programming effort (over one-man year) and computer time (several thousands of dollars) will be required to alter the EPA mathematical model to determine if in modified form it will adequately reproduce the true spatial and temporal distribution of dissolved oxygen. In our opinion, this expenditure of time and money is not warranted at this time.

8. EVALUATION OF THE PHYSICAL MODEL

8.1 *Introduction*

The U.S. Army Corps of Engineers constructed a physical model of Grays Harbor at its Waterways Experiment Station in Vicksburg, Mississippi. Verification and base tests of this model were described by Brogdon (1972a) and Brogdon and Fisackerly (1973). As part of the overall study, the navigation channel in the model was physically altered to approximate the dimensions of the proposed widening and deepening project (Brogdon, 1976).

8.2 *Model Measurements*

The physical model is *three-dimensional* and permits evaluation of circulation patterns which cannot be evaluated from spot measurements in the prototype. It is useful for assessing physical processes, the distribution of conservative properties and changes which result from modifying the navigation channel dimensions such as the proposed widening and deepening project.

Specific measurements obtained during the physical model studies for the *before* and *after* (pre- and post-dredge) bottom configurations included: 1) salinity and currents at the surface, mid-depth and bottom at 45 locations, 2) upstream and downstream transport and dispersion of dyes introduced into the source oceanic water at the Harbor entrance and into the Chehalis River at Cosmopolis, and 3) tide heights at 10 locations. Most, but not all, of these parameters were measured for different stages of the tide and for three river flows (1,270, 11,400, and 37,500 cfs). The *before* tests were compared with actual field data and excellent verification was achieved for tide heights, currents, and salinity distribution. Mosaic photographs of the movement of particles floating on the surface of the physical model for different tide and river stages presented synoptic views of surface currents and circulation patterns. The data obtained from the physical model studies are useful to describe, 1) salinity stratification, 2) current layering, and 3) dispersion of material in the different layers.

8.3 *Model Limitations*

The physical model was not capable of reproducing meteorological effects which in turn affect circulation and mixing processes. No studies were conducted to vary the incoming salinity to reflect changes in oceanic

source water such as occurs during the upwelling season or during the winter when the Columbia River plume extends north along the coast. The physical model cannot portray the distribution of biologically influenced properties as dissolved oxygen (DO). The physical model currently suffers another severe limitation in that the cement foundation of the model has shifted and is no longer suitable for studies without costly re-building and re-verification.

8.4 *Model Results*

Results for the *pre-dredge* channel configuration showed that at all river flows, some salinity stratification occurred in the inner harbor. The highest observed salinities corresponded to the lowest river flow (1,270 cfs). The greatest salinity stratification occurred at mean river flow (11,400 cfs). Between Aberdeen and Cosmopolis, the salt water was completely flushed out at high river flow (37,500 cfs).

Current measurements and dye observations indicated a net sewward flow at the surface and a net landward flow at the bottom. Dye released into the surface waters at Cosmopolis moved seaward and was more concentrated at the surface than at depth. Dye released at the Harbor entrance moved upstream near the bottom. Observations at several stations clearly indicated the importance of tide stage in measuring the distribution and concentration of the dye.

Model studies of the dredged bottom configuration showed similar patterns of salinity, currents and dye dispersion (Brogdon, 1976). A comparison of the *before* and *after* data indicated that for low river flow the salinity regime remained essentially unchanged at all locations and all depths. For the mean river flow, the bottom water between Aberdeen and Cosmopolis was more saline in the *after* condition than in the *before* condition. However, the salinity values obtained for the low flow conditions were higher than those at the mean flow.

Current measurements made for the *post-dredge* configuration indicated enhancement of the net-seaward flow at the surface and the net landward flow at depth. Dye studies made in the *post-dredge* configuration emphasized the enhancement of the two-layer system within Grays Harbor. Dye injected near Cosmopolis at mean river flow was delayed about one day in transiting the estuary under *post-dredge* conditions with the delay occurring

in the eastern half of Aberdeen Reach.

Brogdon (1975 and 1976) evaluated the use of groins along the southern edge of the navigation channel in the inner harbor for 35-foot and 45-foot deep channels (depths referenced to mean sea level). The intent was to direct the flow so as to decrease sedimentation. The groins in the model increased mixing, reduced salinity stratification, and reduced salinity concentrations east of Hoquiam. More fresh water was stored in the inner Harbor and a longer residence time resulted. The use of groin fields as tested in the model are not a part of the present plans for the widening and deepening project.

9. IMPACTS OF THE PROPOSED WIDENING AND DEEPENING PROJECT ON WATER CHARACTERISTICS

9.1 *Introduction*

The proposed widening and deepening of the navigational channel in Grays Harbor will increase the cross-sectional area of the channel and the total volume of the estuary. This will be especially true of the channel upstream of Moon Island. Since the intertidal volume and river discharge will not be affected, the speed of the mean current in the channel will be decreased in proportion to the increase in cross-sectional area. This slowing of the mean current would tend to increase the residence of the water in the dredged regions. However, other factors altered by the dredging may improve the flushing characteristics, thus compensating for the increase in residence time.

In assessing the effects of dredging upon the water characteristics, the existing water characteristics data were utilized to describe the present (or *pre-dredged*) conditions in Grays Harbor (see Chapter 3). These data and the results from the physical model were used to make predictions concerning the effects of the dredging project upon water characteristics. It was not the objective of this study to assess the impacts of the proposed project upon the water during the actual dredging phase.

Physical and mathematical models have different purposes and capabilities. Physical models are used primarily for evaluation of processes affected by tides, river flow, and basin configuration. A physical model is *three-dimensional* and observations may be made at any location, at any instant of time both past and future, for any given tide stage, and for any river flow. Physical models show circulation patterns, effect of channel configuration upon circulation, movement of water parcels and changes in conservative properties (such as salinity) which are not affected by biological processes. Density stratification of the water column may be created by introducing varying concentrations of salt water and changing the river flow rate. The bottom configuration may be altered and the resulting changes in circulation and distribution of conservative properties may be compared to those observations made with the original bottom configuration. However, a physical model can not duplicate the effects or wind nor can it be used to evaluate non-conservative properties (such as dissolved oxygen) which are biologically dependent.

A mathematical model permits factors affecting biological dependent properties to be changed. A major limitation of most mathematical models is that they treat a system as *one-dimensional* by integrating the properties over the entire volume of each segment and use this value as a single point along the axis of the channel. Very few mathematical models account for vertical stratification of the water in both the vertical and horizontal. Also such models are usually adjusted to reproduce conditions for a specific period of time. Since many of the variables affecting dissolved oxygen (DO) are time dependent, any results extrapolated to another period of time may not be valid. Results obtained from any mathematical model are dependent upon a good understanding of the variables affecting the desired property, in this case dissolved oxygen, and the nature of the equations to compute this variable.

A physical model of Grays Harbor was constructed by the U.S. Corps Army of Engineers and the results are discussed in chapter 8. The mathematical model developed by the Environmental Protection Agency (Region X) is discussed in chapter 7.

9.2 *Effects of the Proposed Project*

The physical model studies that specifically evaluated the effects of the proposed widening and deepening project upon the circulation patterns and on the physical processes in Grays Harbor are excellent and are are well described. How these changes in physical processes and the distribution of conservative properties predicted by the physical model may affect DO is subject to interpretation. Our interpretation follows.

Changes in the volume of water in the segments of Grays Harbor resulting from the proposed dredging project are presented in Table 9-1. The volume changes in the affected segments of Crossover and Moon Island Reaches were small (3% and 9% respectively) and increased to 15% in Hoquiam and Cow Point Reaches and the western half of Aberdeen Reach. However, the volume change was most pronounced in the eastern end of Aberdeen Reach from Junction City to Cosmopolis where the volume would be increased by 27%. Much of this increase is produced by the enlarged turning basin to be dredged here.

Between Hoquiam and Cosmopolis an oxygen depression ("DO sag") is often developed expecially during low river flows, below about 3,500 cfs. Naturally derived organic matter from within the estuary and from upstream sources as well as industrial and municipal sources of oxygen- consuming organic matter,

TABLE 9-1

CHANGES IN VOLUME BY THE PROPOSED WIDENING AND DEEPENING OF INNER GRAYS HARBOR

Reach	Model Division No.	Old Volume (cubic feet)	Change in Volume (cubic feet)	Percent Change
Cross-Over	6 & 7	1,724,873,000	57,431,000	3%
Moon Island	8 & 9	1,022,521,000	90,919,000	9%
Hoquiam	10 & 11 & 12	616,538,000	93,398,000	15%
Cow Point	34	289,377,000	37,086,000	13%
Aberdeen, West	35 - 39	531,914,000	64,404,000	12%
Aberdeen, East	40 - 44	364,320,000	67,953,000	27%
		4,549,543,000	411,191,000	

In the physical model, dye dispersion studies to evaluate the effects of the proposed dredging project were made only at the mean river flow (11,400 cfs). Dyes with densities equal to the receiving waters were injected at two sites, one near Cosmopolis and the other in the entrance of the harbor. Dye released at Cosmopolis flowed seaward at the surface while dye released in the entrance of Grays Harbor moved upstream with a two-layer system being developed. Deepening of the model channel allowed more oceanic water to enter the inner harbor.

In summer, the inflowing oceanic water entering the outer harbor will be cooler, more saline and lower in DO than the estuarine water. Its effect upon the waters of the inner harbor will be to slightly cool the outflowing surface layer and possibly reduce its DO content. Data were not available to evaluate this effect upon the waters of the inner harbor. However, from our interpretation of Callaway's (1971) steady-state model approach to evaluating the significance of upwelled water and from the salinity data obtained from the physical model studies, we conclude that coastal upwelling will not influence the DO east of Aberdeen where the volume changes due to dredging will be the greatest.

Density and salinity stratification, natural phenomena in estuaries, will be encouraged in the inner harbor by the proposed dredging project especially for mean river flow. This effect will be most evident in Hoquiam and Aberdeen Reaches. Stratification further upstream, especially upstream of Hoquiam, may break down during low river flow because of tidal dominance. The physical model indicated that no increase in upstream salt water intrusion would occur due to dredging. This region of the estuary is normally "well-mixed" but during the summer after dredging is completed, it may become "partially-mixed", At high river flows (37,500 cfs), the physical model indicated that salt water would be nearly flushed out of the inner harbor. The same effect was also evident from the actual water characteristics as is evident from the large variability in salinity that occured with season, river flow, and tide stage (see Figs. 3-9 through 3-23 and 3-27).

An increase of cross-channel area due to dredging will impede flushing in the absence of a two-layer system. However, if a two-layer system results from the proposed dredging, the seaward surface flow in the inner harbor will be increased and will equal the combined river discharge and flow of salt water entrained into the fresher surface layer. An additional landward flow

of salt water at depth must occur to replace the salt entrained in the surface flow. The effects of increased cross-sectional channel area will be to reduce the speed of the currents in a non-layered system. But an increased two-layer flow will tend to compensate for the increased area in all but the eastern most end of Aberdeen Reach. The residence time in this reach will be increased about one day. Results from the physical model support this conclusion. It is significant to note that the principal industrial and municipal discharges occur several miles downstream from Cosmopolis. Hence, an increase in flushing time of one day in the eastern end of Aberdeen Reach will not significantly influence the dispersion of wastes or highly influence their transport in the region where the "DO sag" occurs.

Increased residence time in the eastern end of Aberdeen Reach can be significant when oxygen consuming material arrives from upstream sources or is discharged within this Reach. Most of the upstream material is naturally derived and may exceed the local contribution. A slightly lower DO within Aberdeen Reach may result from the increased residence time of organic material passing from the river into the estuary. But this may be offset by the enhancement of the two-layer flow and by increased volume of water available to assimilate any oxygen consuming material. It is not possible for the physical model to test this hypothesis as DO is non-conservative. Improvements in municipal and industrial waste treatment practices since 1975 have greatly reduced the amount of BOD and COD entering Grays Harbor. As a result, the DO within the inner harbor may now be approaching conditions which could be considered to be "natural".

From this discussion of the actual data and model studies, *it is our conclusion that the proposed widening and deepening of the navigation channel in Grays Harbor will have no significant impact upon the water characteristics*. Although our evaluation of the proposed dredging project examined only the maximum size channel, a channel of lesser size would also have no significant impact.

AD-A095 390 WASHINGTON UNIV SEATTLE DEPT OF OCEANOGRAPHY F/G 8/8
A REVIEW OF WATER CHARACTERISTICS OF GRAYS HARBOR 1938-1979 AND--ETC(U)
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10. RECOMMENDATIONS FOR FURTHER STUDIES

If the proposed widening and deepening project of the navigation channel in Grays Harbor is carried to completion, there will be need for additional sampling of water characteristics to compare the existing (or *pre-dredged*) data base with the postdredge conditions. At present, we can only estimate the impacts of such a project on the water properties of Grays Harbor. Hence, "after-the-fact" monitoring is essential to determine what the actual impacts on water characteristics will be and to verify or refute the estimates based upon available data and models. Such documentation will be of tremendous use in future dredging projects in this and other estuaries as it will help settle the question surrounding the applicability of models as predictive tools.

Any future water characteristic sampling programs, either *before* or *after* dredging, should include all of Grays Harbor from its mouth to 3 miles upstream of Comospolis. Parameters to be measured should include temperature, salinity, dissolved oxygen (DO), and spent sulfite liquor (SSL). These observations must be *synoptic* and obtained near high tide.

The "DO sag" (see Figs 3-9 and 3-10) has been a major concern and traditionally has been viewed in the literature as a spatially static feature. Because of recent advancements (since 1975) in the treatment of municipal and industrial wastes being discharged into Grays Harbor, the "DO sag" no longer appears to be a major problem. The "DO sag" is a dynamic feature which has not been adequately studied or understood. We feel that the dynamics of the "DO sag" must be more critically examined. Extensive sampling in the inner harbor (Fig. 2-2) will be necessary at different river flows and for spring and neap tides. At least ten stations along the channel axis should be occupied hourly for a minimum of 25 hours each period. Dissolved oxygen should be determined by a modified Winkler method rather than by the use of electronic sensors (probes). During the summer, sampling should be extended to the entrance of Grays Harbor to determine if upwelling occured and to evaluate its influence on DO. These studies should be conducted *before* and *after* the proposed widening and deepening project. The *before* data

will provide information needed

1) to describe the dynamics of the "DO sag",
2) to assist in further predictions of possible impacts of the dredging project on water characteristics, and
3) to provide the necessary data base to compare the *after* conditions with the present (*before*) conditions.

The physical model studies, described in chapter 8, should have included dye dispersion studies during low river flow conditions for the original basin configuration and again after the basin was altered by the proposed dredging project. This would have assisted in assessing changes of flushing processes between Aberdeen and Cosmopolis at a time when these processes are primarily tidally driven. Because the existing physical model will require considerable repairs, to make it usable, the authors do not recommend that the model be refurbished just to obtain these data.

The mathematical model as it now exists (see chapter 7) is not suitable for the prediction of the DO distribution in Grays Harbor. We do not recommend futher efforts in mathematical modeling because of the excessive programmer time and computer expense necessary to account for the very involved dynamics of Grays Harbor.

In summation, since the available predictive tools and the assesment of available data indicate that no major changes in water characteristics will occur as a result of the widening and deepening of the navigation channel in Grays Harbor, we conclude that the impact of such a project will be minor. The proof of this conclusion can only be made by comparing "after-the—fact" data with the existing data base.

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